Searching for new physics from a dark sector using levitated microspheres

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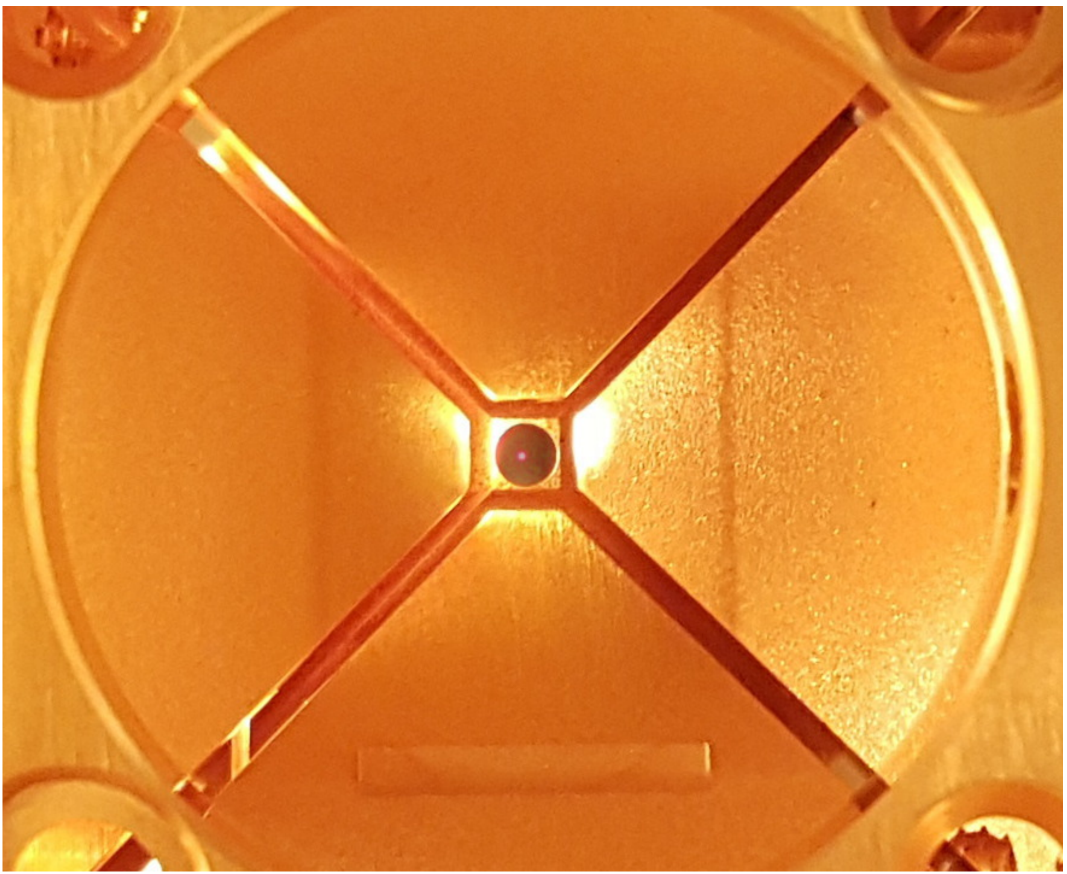
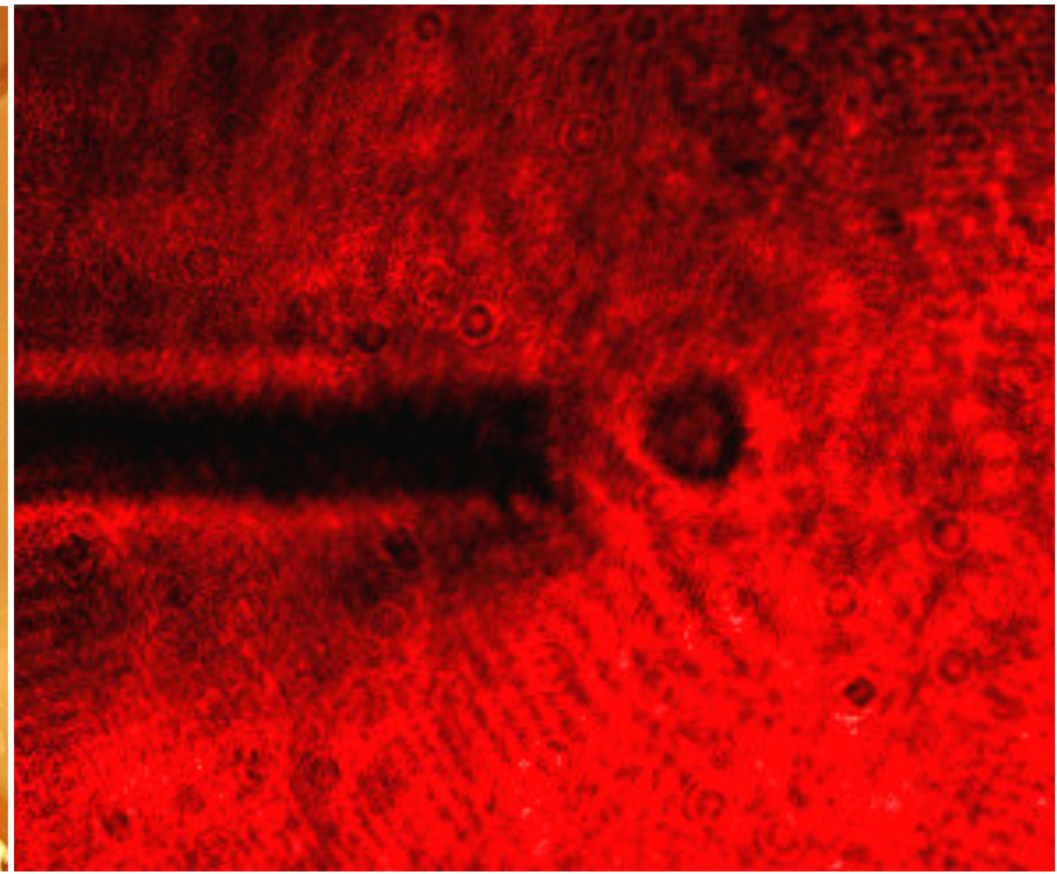




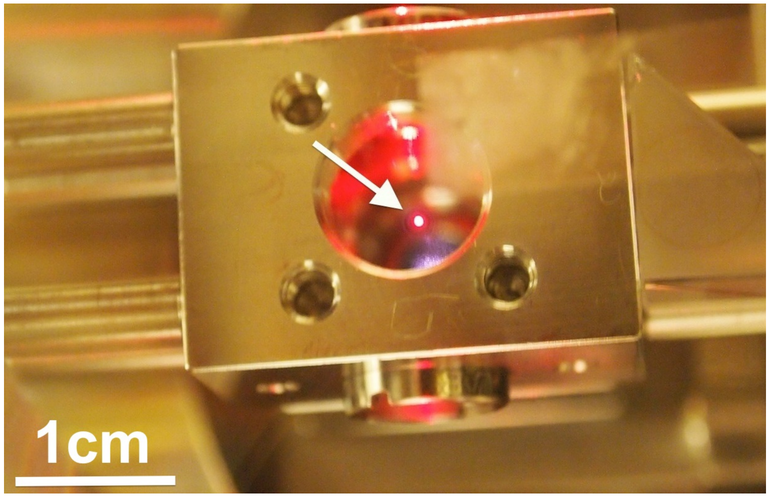
Optical levitation

- New forces at << mm distances appear in a variety of models of new physics
  - Non-Newtonian forces at μm distances (hierarchy problem, dark energy)
  - Hidden sector dark matter models (millicharged particles, dark photons)
- Levitate ~μm spheres in high vacuum and look for new forces at << 100 μm
- At high vacuum, extremely low dissipation is possible:

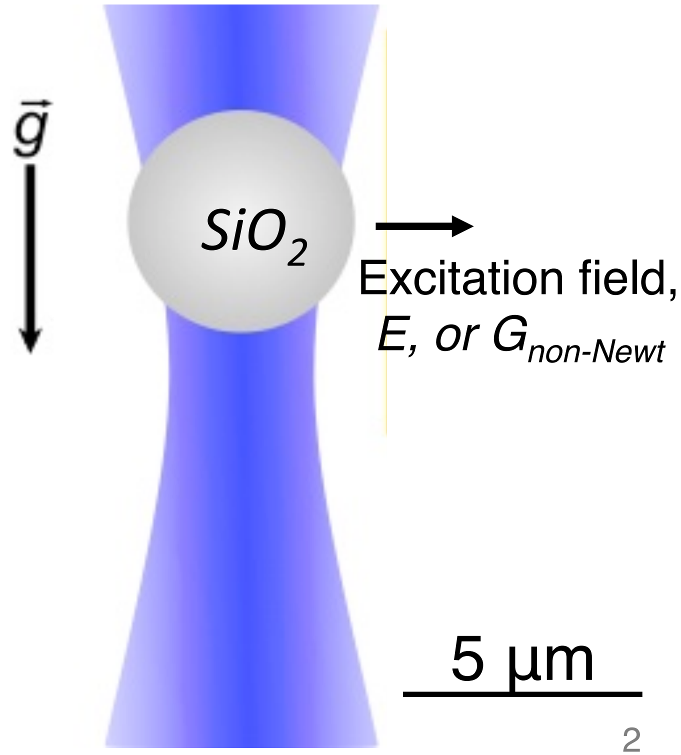
  $\sigma_F \sim 10^{-21}$ N Hz$^{-1/2}$ at 10^{-10} mbar

  Near "standard quantum limit" for ~μm size masses

Photograph of trapped microsphere:



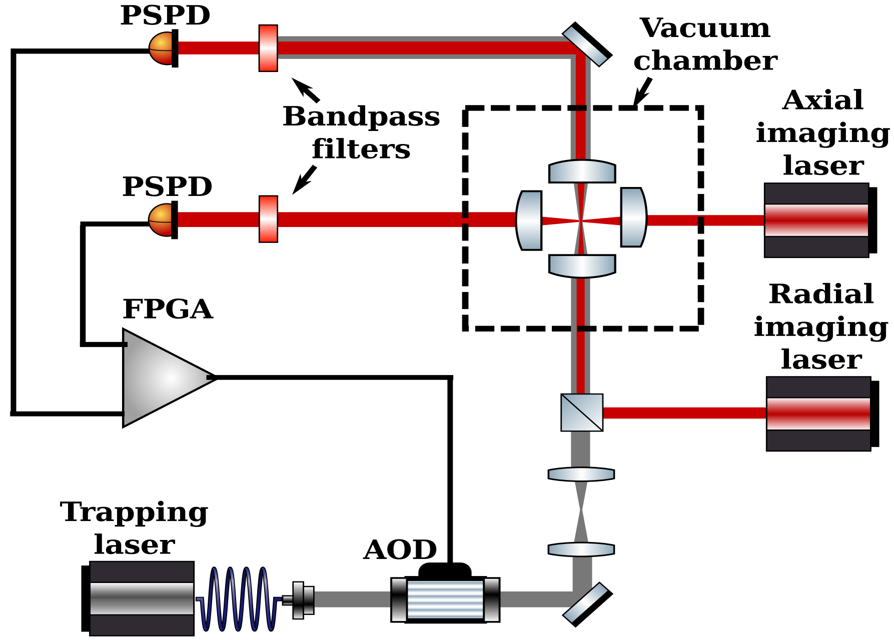
Schematic of optical levitation technique:



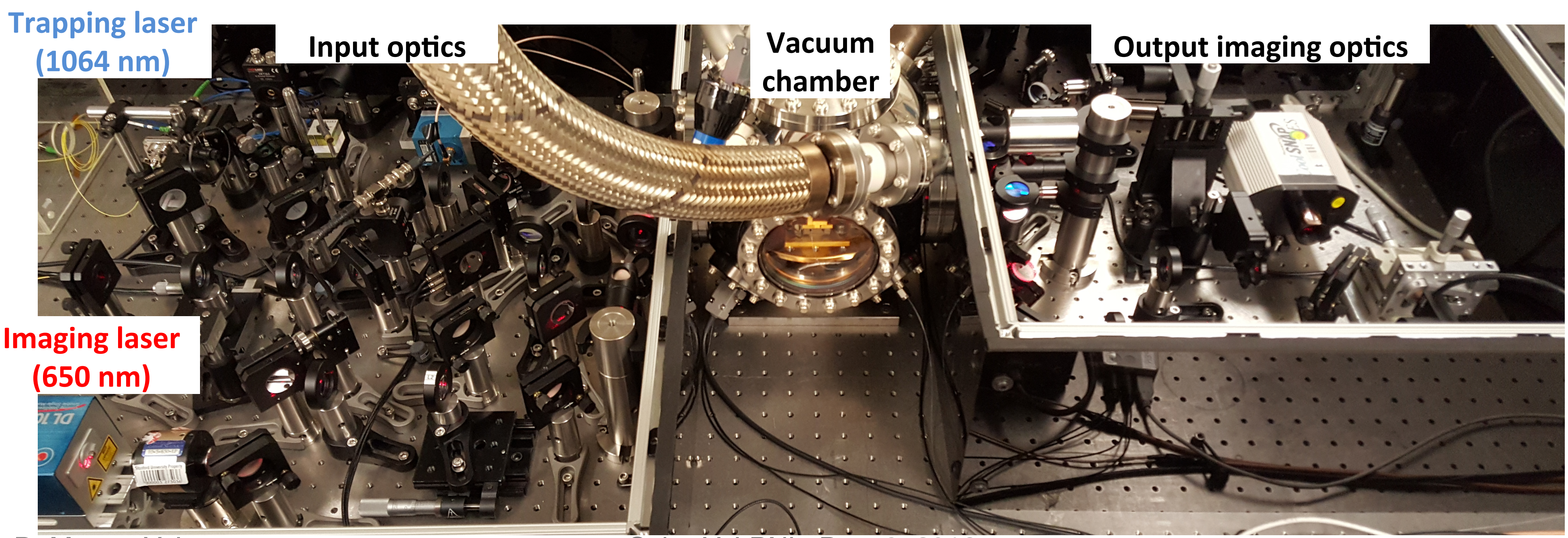
Experimental setup

- Developed setup capable of levitating SiO_2 microspheres with r = 0.5-5 μm
- Microspheres are levitated in vacuum chamber with λ = 1064 nm, ~few mW trapping laser
- Have demonstrated trapping times of >2 weeks at ~10^{-7} mbar

Simplified optical schematic:



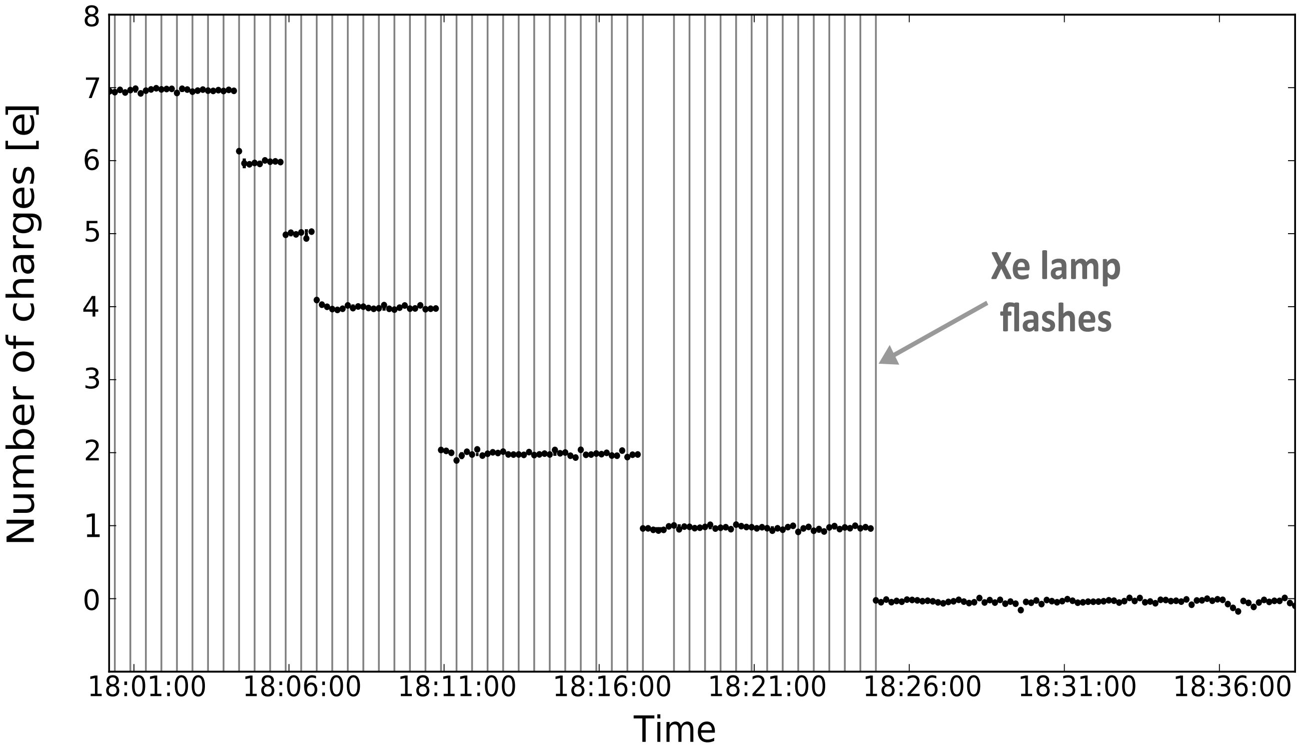
Photograph of experimental setup:



Microsphere neutralization

- Have demonstrated controlled discharging with single e precision
- Measure microsphere response to oscillating electric field while flashing with UV light
- Allows absolute calibration of force sensitivity, $\sigma_F \sim 10^{-17}$ N Hz$^{-1/2}$ ($\sigma_a \sim 100$ μm/s^2 Hz$^{-1/2}$)

Example of discharging process:



Electrode cross-section:

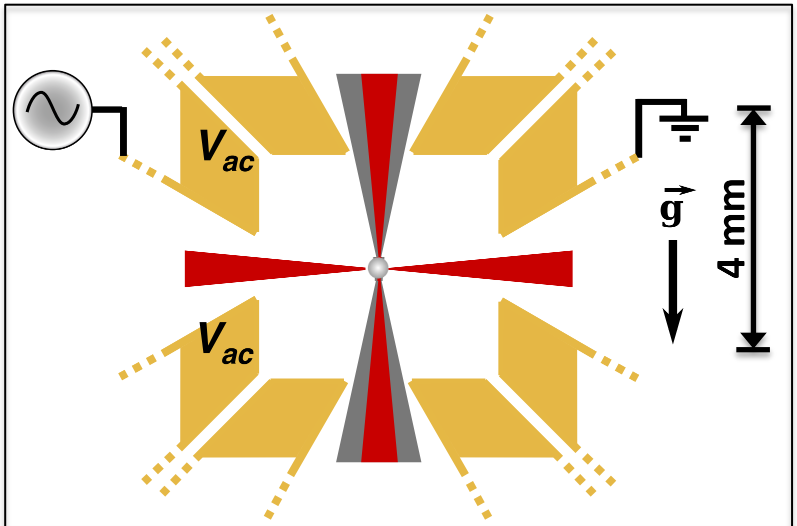
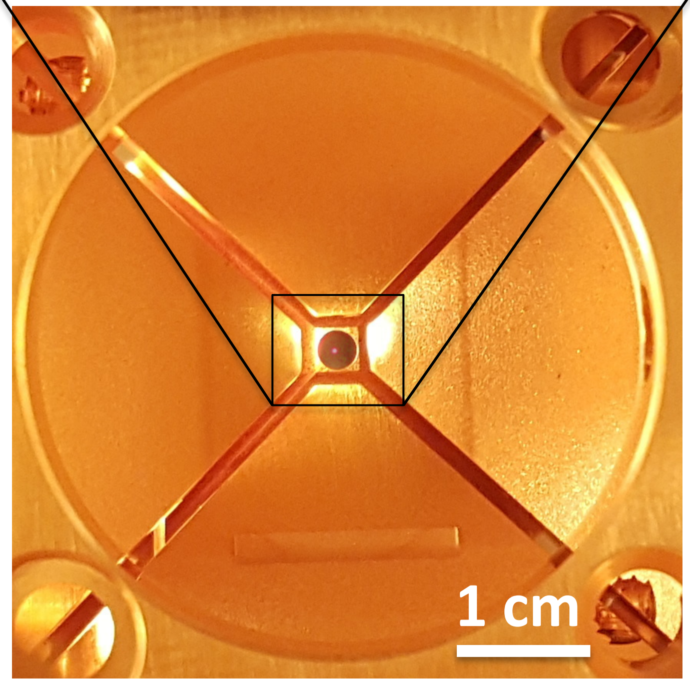


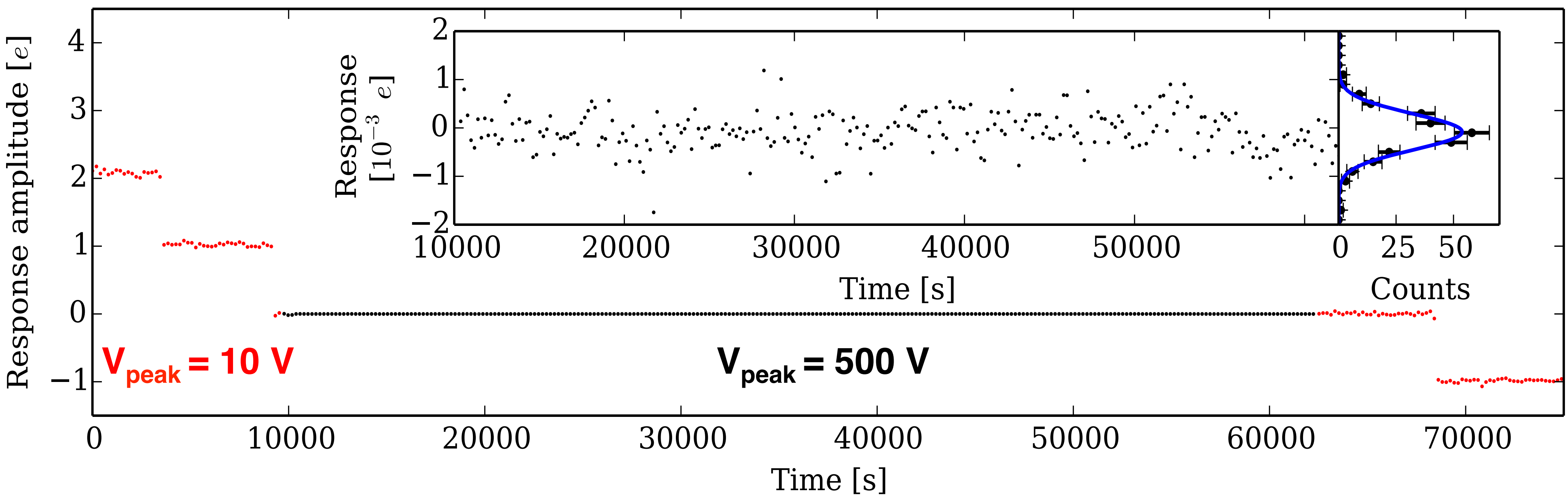
Photo of electrodes:



Microsphere neutrality

- Have performed a search for millicharged particles (|q| << 1e) bound in the microspheres
- Stable, millicharged particles could be produced in the early universe and form bound states that can be searched for in terrestrial matter
- Neutralize microspheres (so that $n_e = n_p$) and search for residual fractional charge

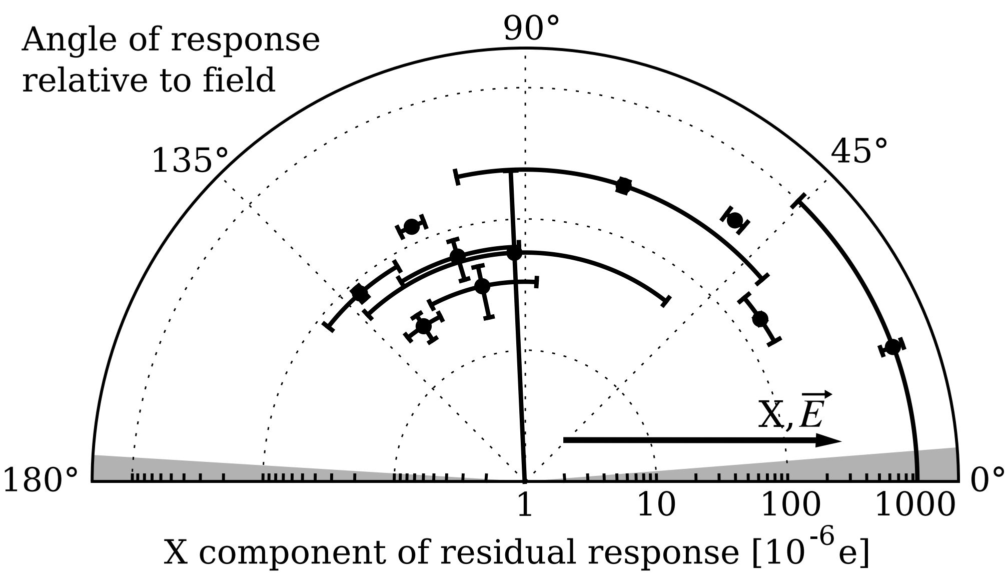
Residual charge measurement for an example microsphere:



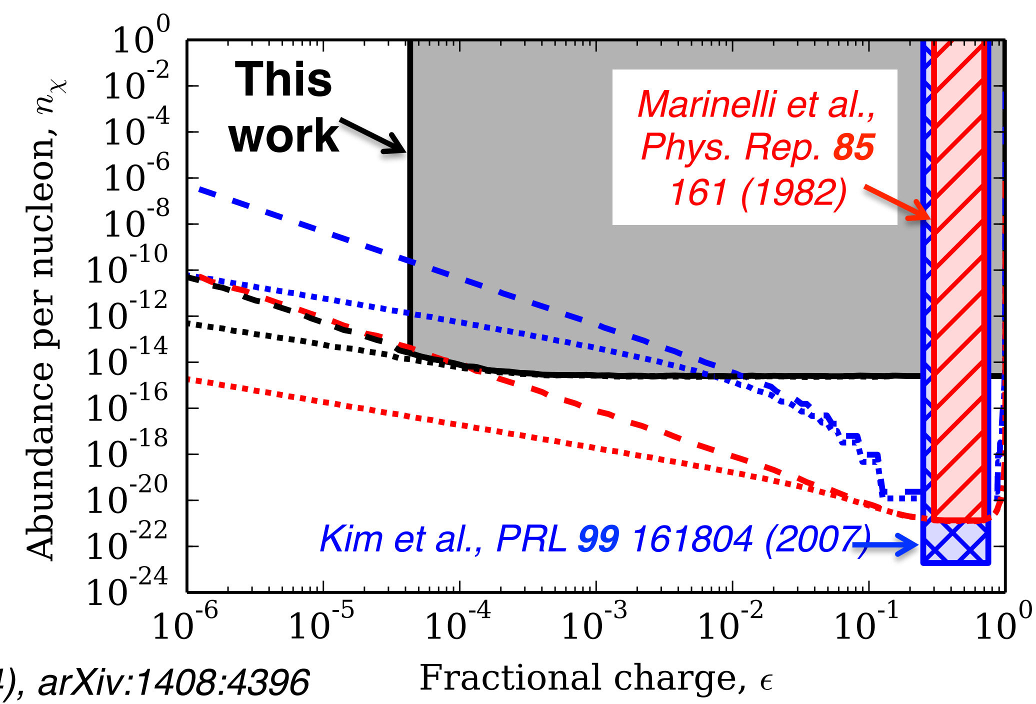
Millicharged particles

- Repeated search with 10 microspheres ($m \approx 0.1$ ng each)
- Statistically significant residual response consistent with permanent dipole coupling to small E-field gradients
- Sensitivity to single fractionally charged particles with charge as small as 5 x 10^{-5} e

Measured residual response:



Limits on abundance of millicharged particles:

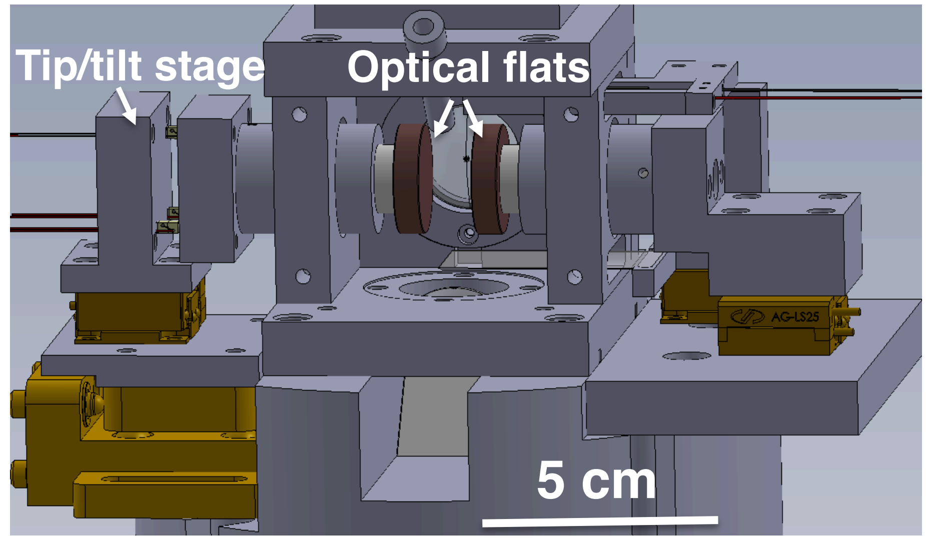


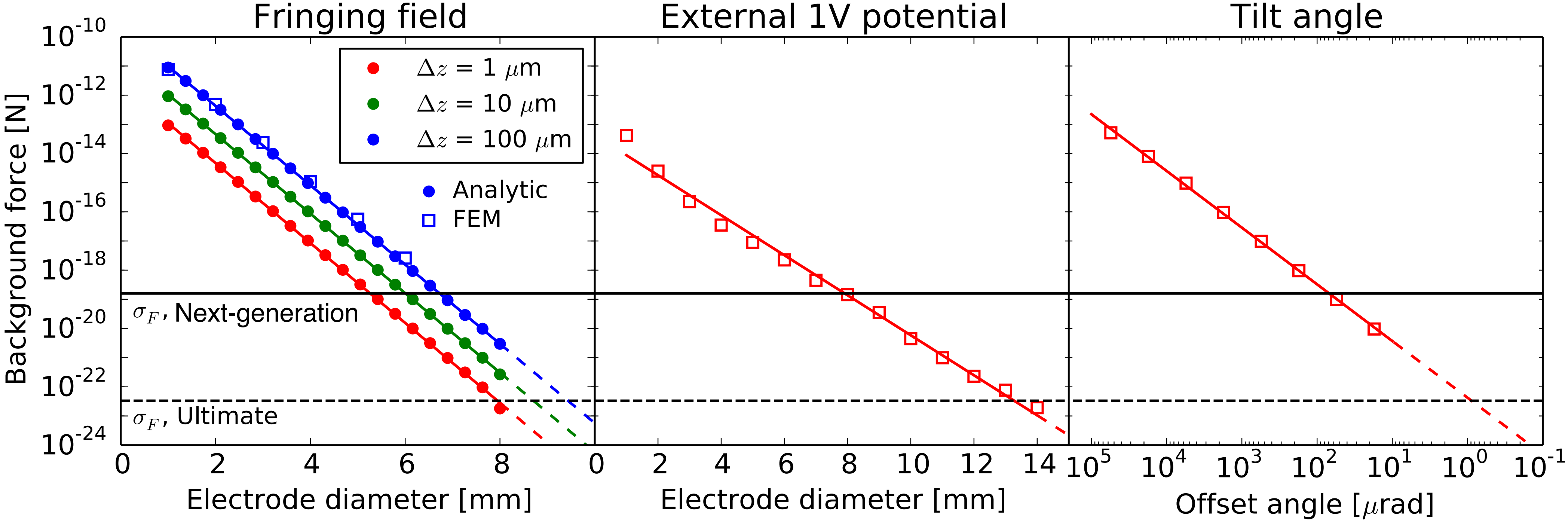
*Moore et al., Phys. Rev. Lett. **113** 251801 (2014), arXiv:1408:4396*

Optimized apparatus

- Primary limitation was backgrounds due to microsphere dipole moment
- Optimized setup can substantially improve field uniformity
- Vacuum tip/tilt stage allows *in situ* alignment to ~100 μrad

Schematic of improved setup:

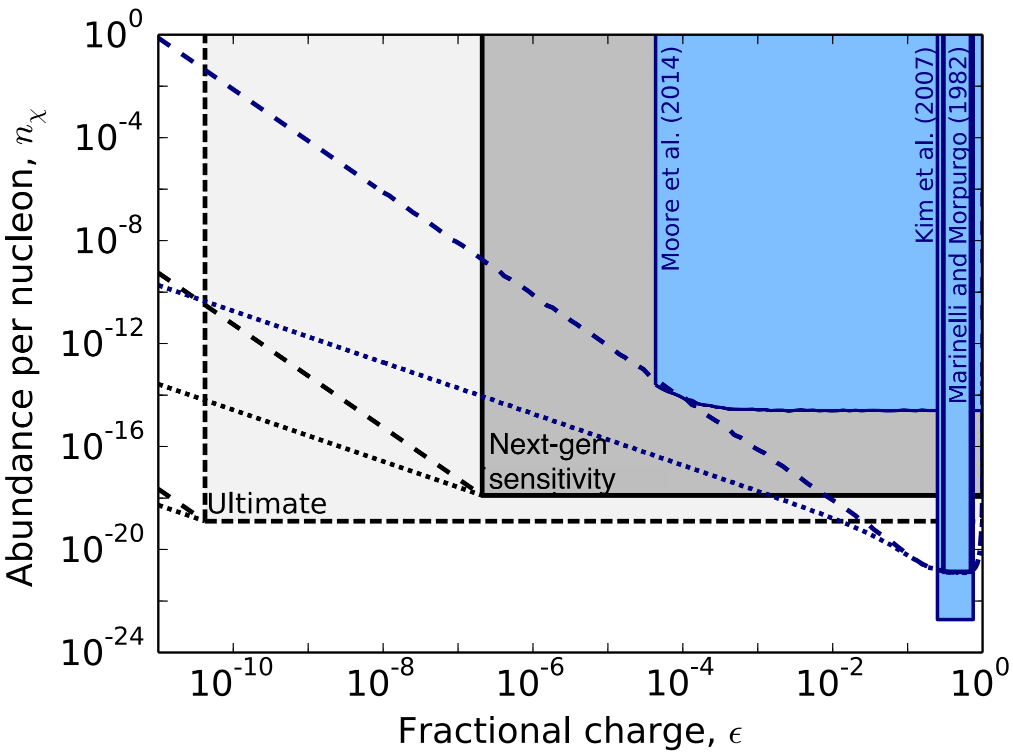




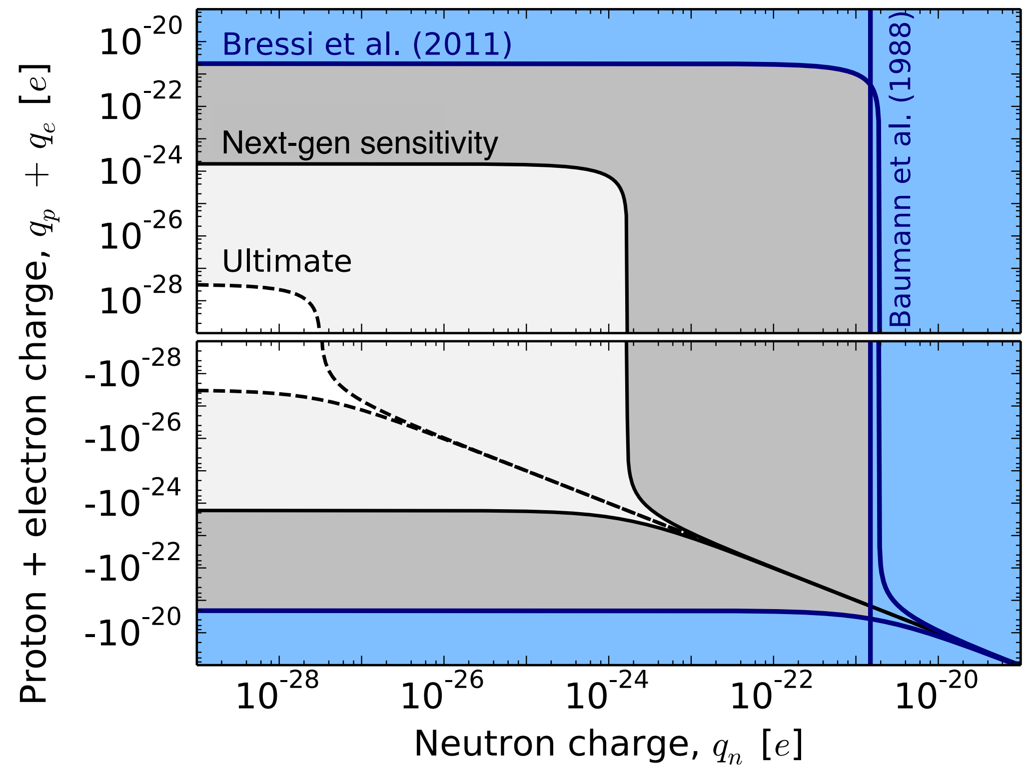
Future sensitivity

- Next-generation experiment aimed at backgrounds below 10^{-19} N for r = 20 μm spheres
- Will allow improved searches for millicharged particles as well as tests of the neutrality of matter ($|q_p + q_e + q_n|$)

Projected sensitivity, millicharged particles:



Projected sensitivity, neutrality of matter:



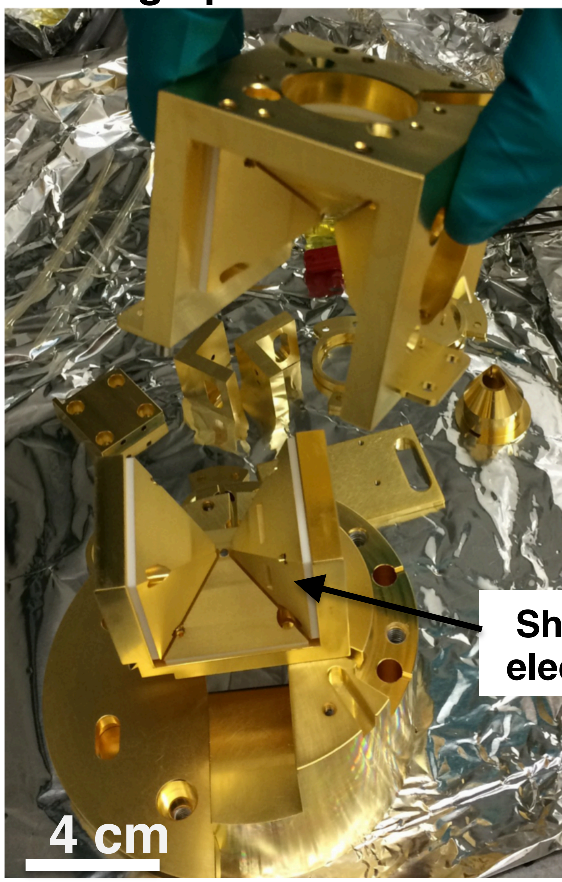
Screened scalar dark energy

- In certain screened scalar dark energy models new forces appear below:

$$\Lambda = 2.4 \text{ meV} \Rightarrow \hbar c/\Lambda \sim 80 \ \mu\text{m}$$

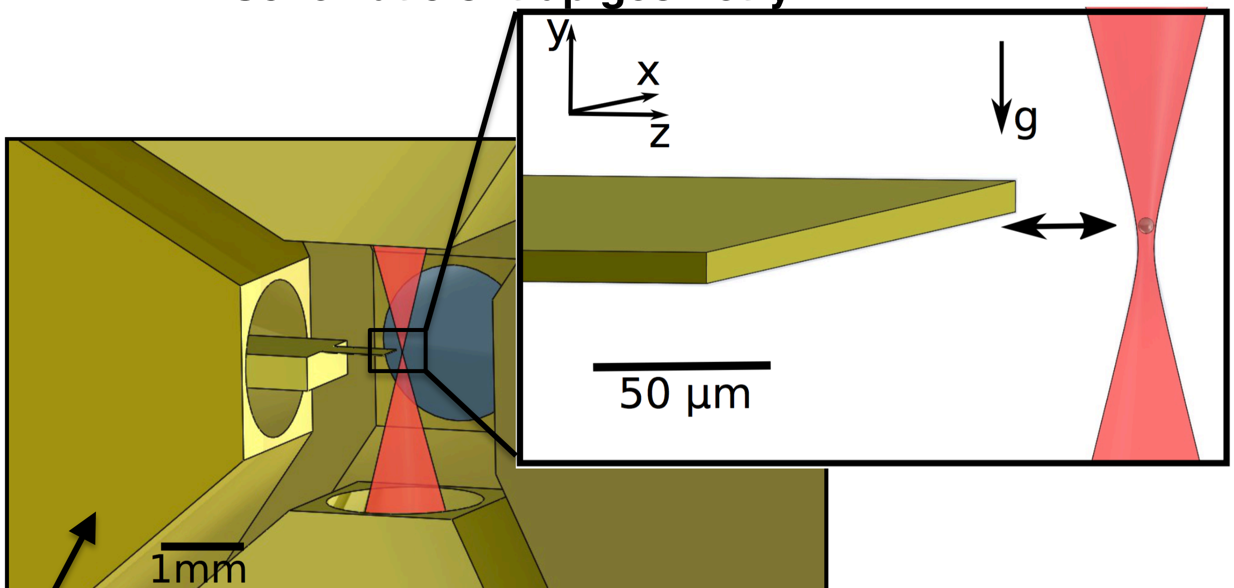
- To search for forces from screened scalars, oscillate mass density near the trap using a Au-plated Si cantilever

Photograph of electrodes:



Shielding electrodes

Schematic of trap geometry:



Experimental parameters:

Microsphere radius [µm]	2.50 ± 0.24
Microsphere density [g/cm^3]	2.0
Cantilever thickness [µm]	10.4
Separation distance [µm]	20 - 230
Background pressure [mbar]	< 10^{-6}

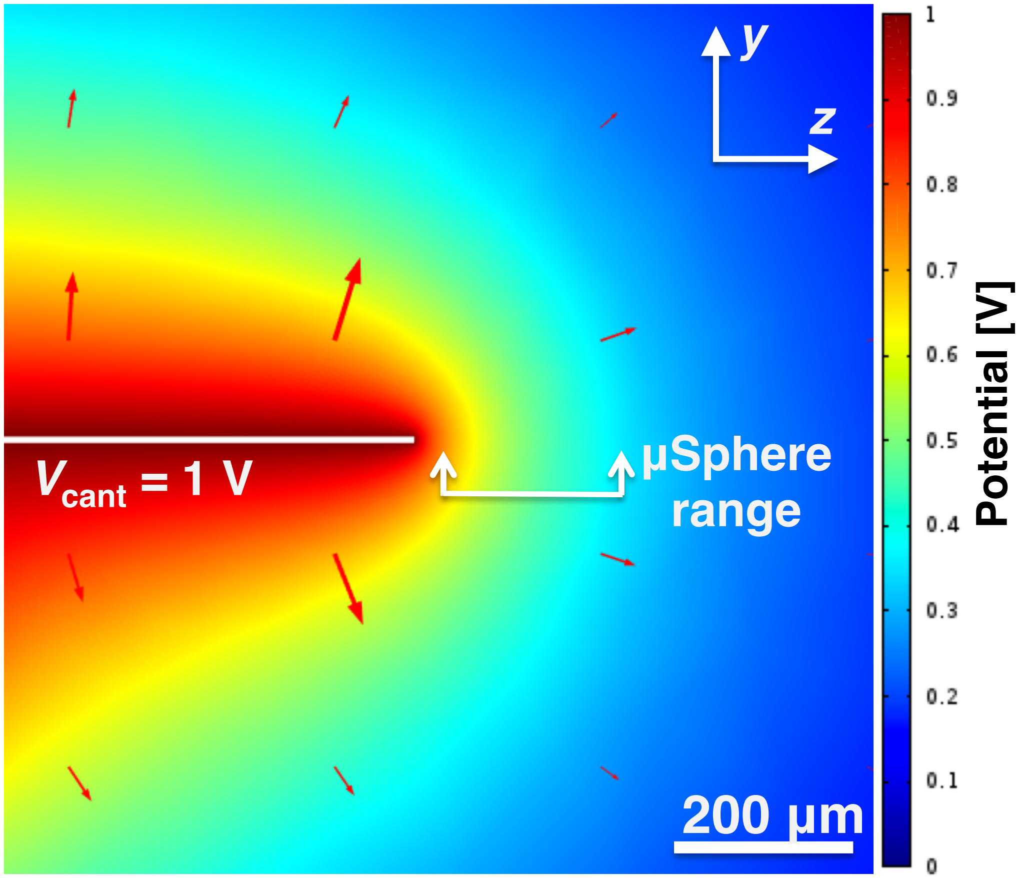
Electrostatic calibration

- Neutral microspheres contain ~10^{14} electric charges and interact primarily as dipoles:

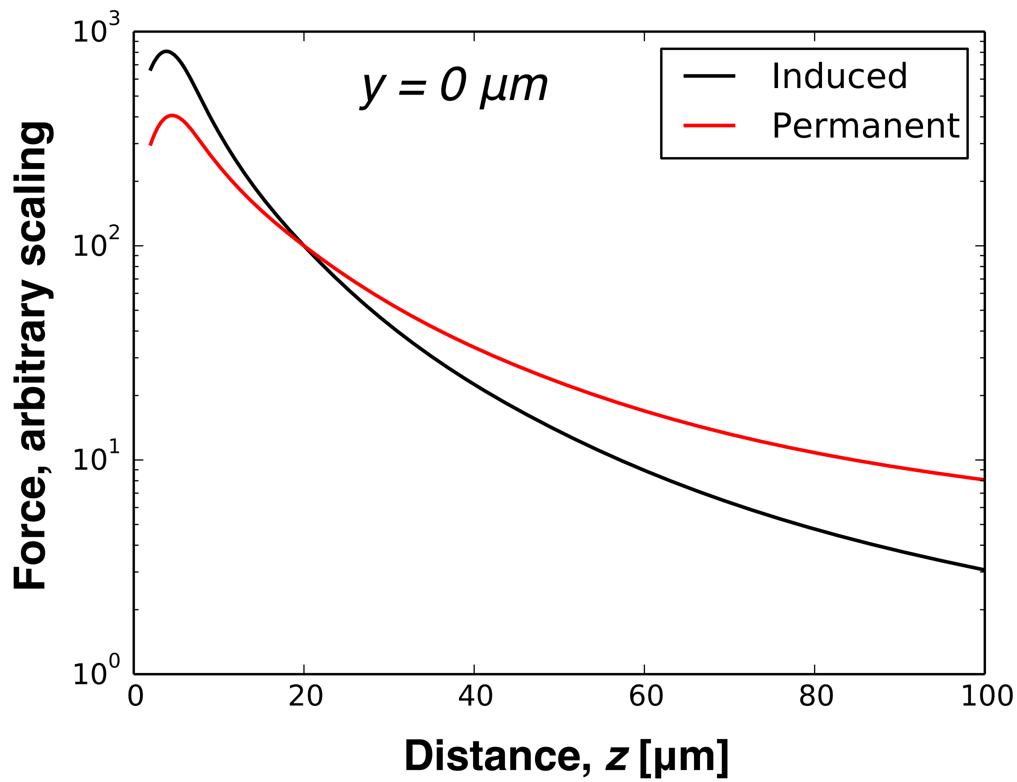
$$\vec{F} = (\vec{p} \cdot \vec{\nabla})\vec{E} \quad \Rightarrow \quad F_z \approx (p_{0z} + \alpha E_z)\frac{\partial E_z}{\partial z}$$

Permanent dipole **Induced dipole**

FEM calculation of electric potential:

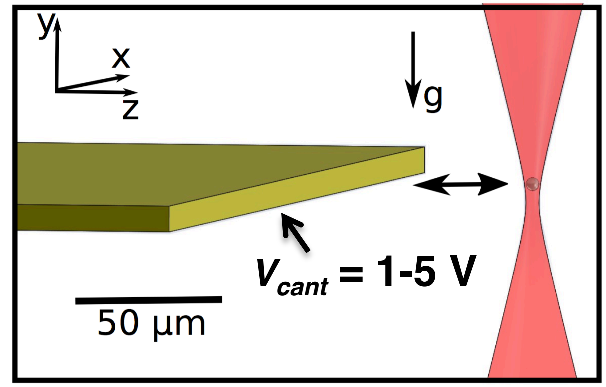


Force for permanent and induced dipole:

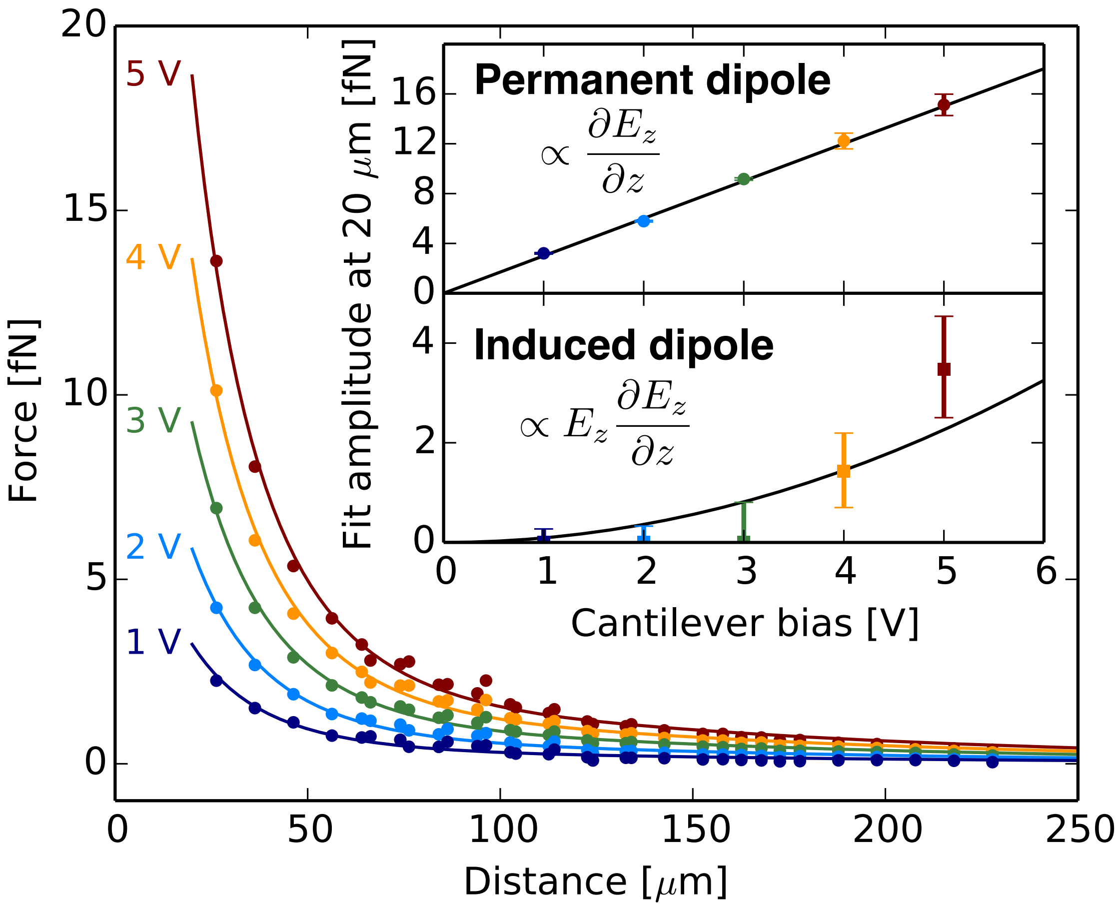


Electrostatic calibration

- Bias cantilever to from 1 to 5 V and sweep its position
- Fits to distance dependence allow determination of permanent and induced dipole moments



Microsphere response vs. distance:



Fits to dipole response:

Microsphere	p_{0z} [$e\,\mu$m]	α/α_0
#1	151 ± 6	0.21 ± 0.13
#2	89 ± 10	0.00 ± 0.33
#3	192 ± 30	0.25 ± 0.14

Polarizability, α, measured relative to:

$$\alpha_0 = 3\epsilon_0 \left(\frac{\epsilon_r - 1}{\epsilon_r + 2}\right)\left(\frac{4}{3}\pi r^3\right)$$

for $\varepsilon_r \approx 3$, r = 2.5 μm

Chameleon force

- As an example, calculated sensitivity to forces mediated by chameleons
- Assume inverse power law potential (n = 1):

$$V_{\rm eff} = \Lambda^4 \left(1 + \frac{\Lambda}{\phi}\right) + \left(\frac{\beta\rho}{M_{Pl}}\right)\phi$$

- Solve equation of motion in full 3D geometry with FEM

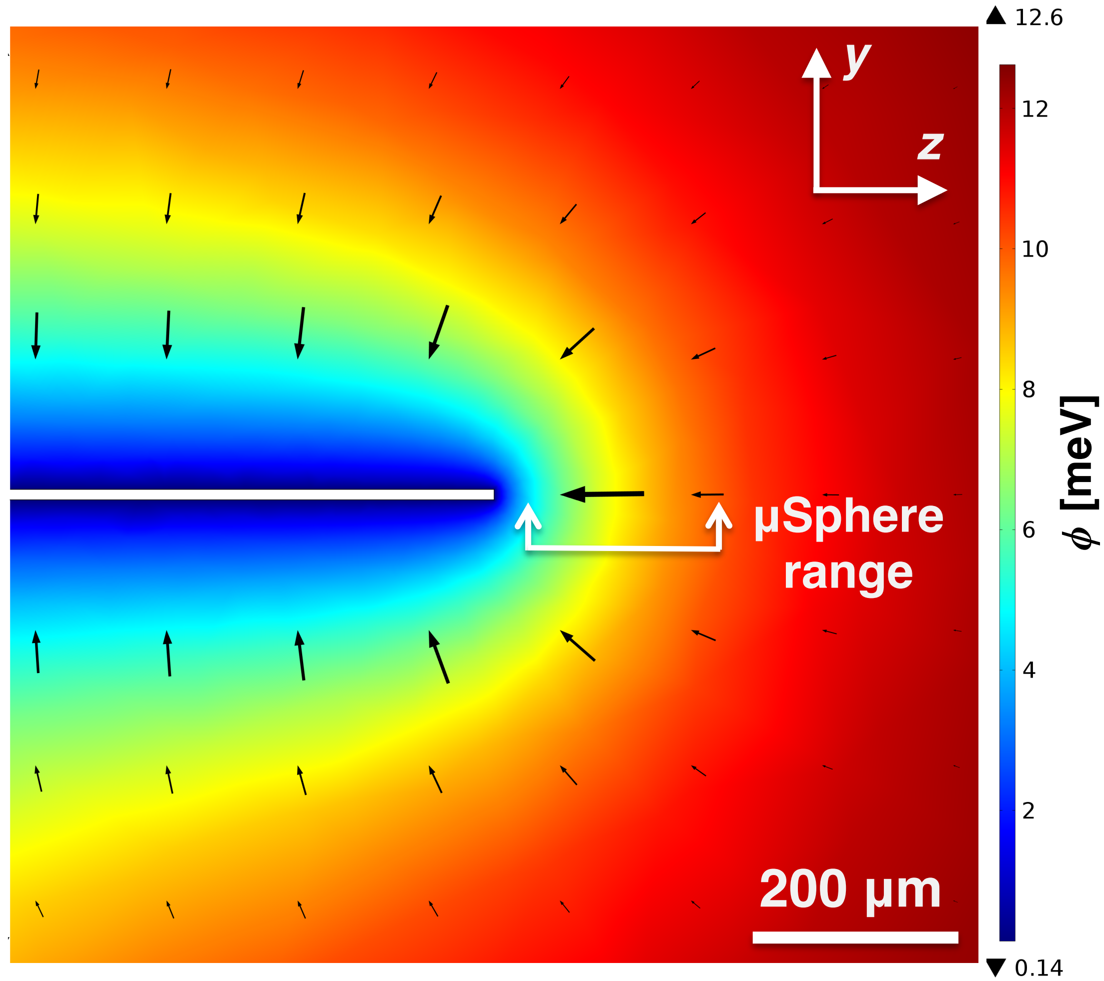
$$\nabla^2\phi = \partial_\phi V_{\rm eff}$$

- Screening negligible when:

$$\rho r^2 \ll \frac{3M_{Pl}}{\beta}\phi$$

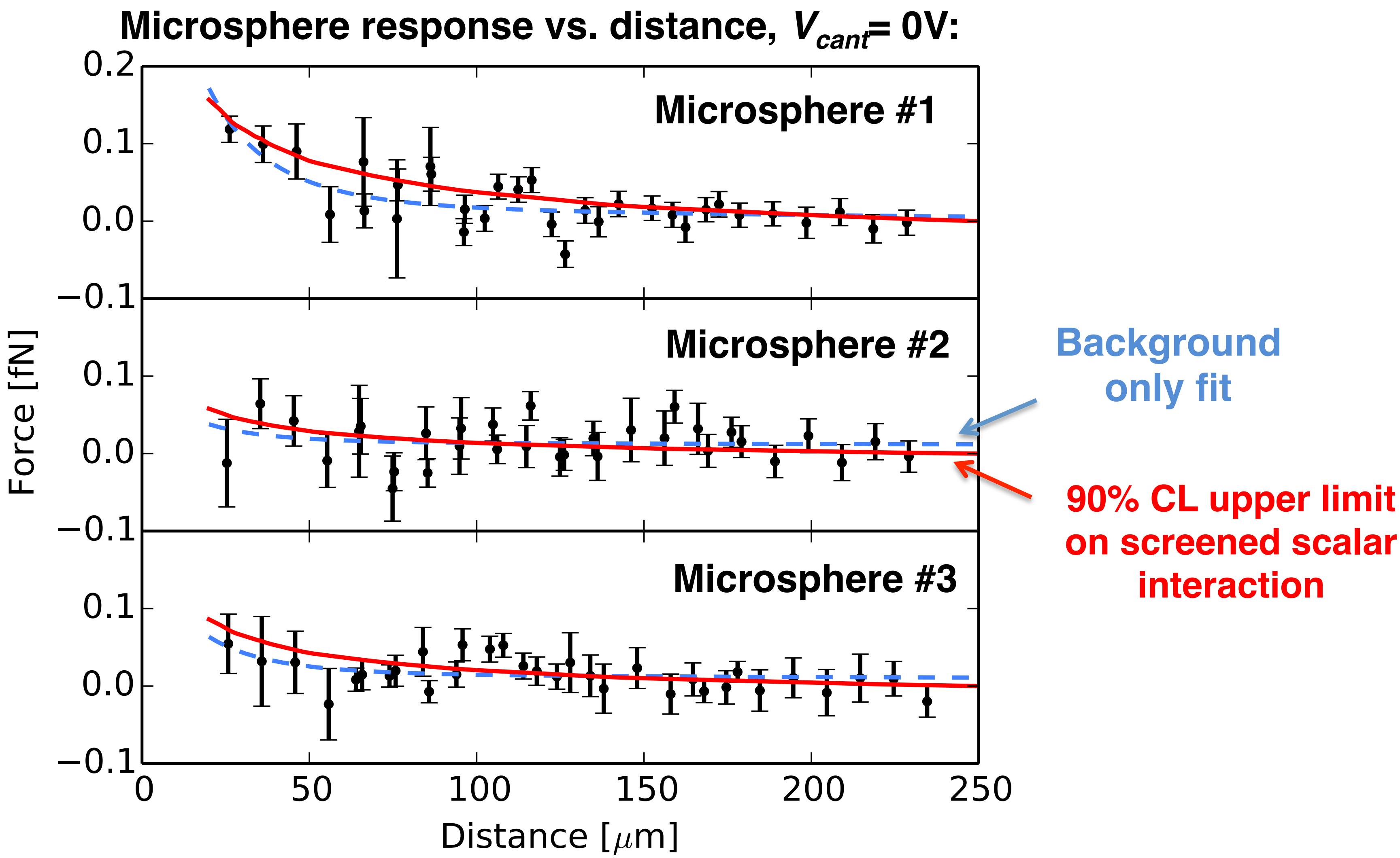
- Fit data to sum of force from chameleon and free electrostatic background

FEM calculation of ϕ:



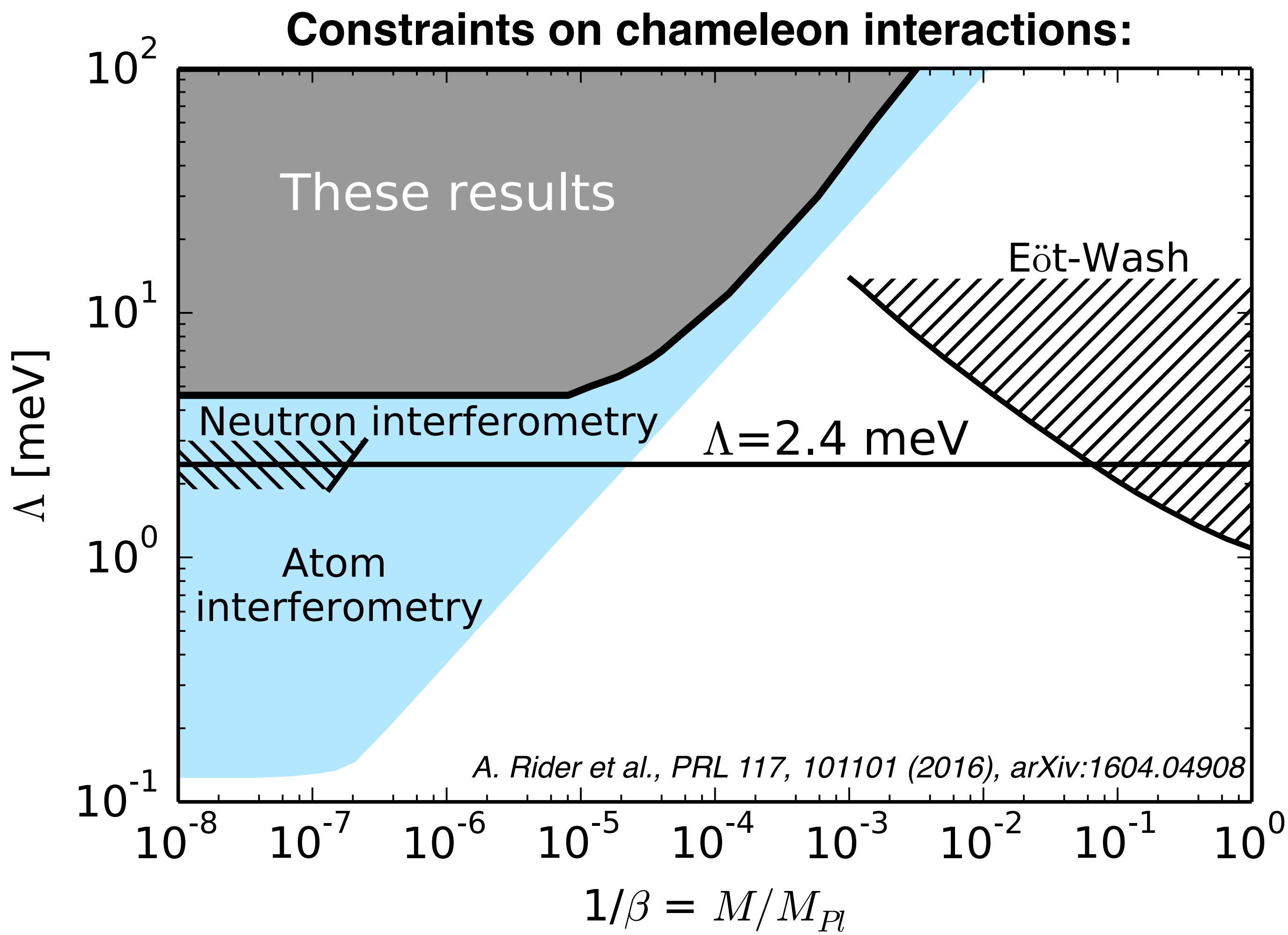
Residual response

- After measuring response to non-zero bias, set to nominal potential of 0 V
- Residual response consistent with <30 mV contact potentials



Constraints

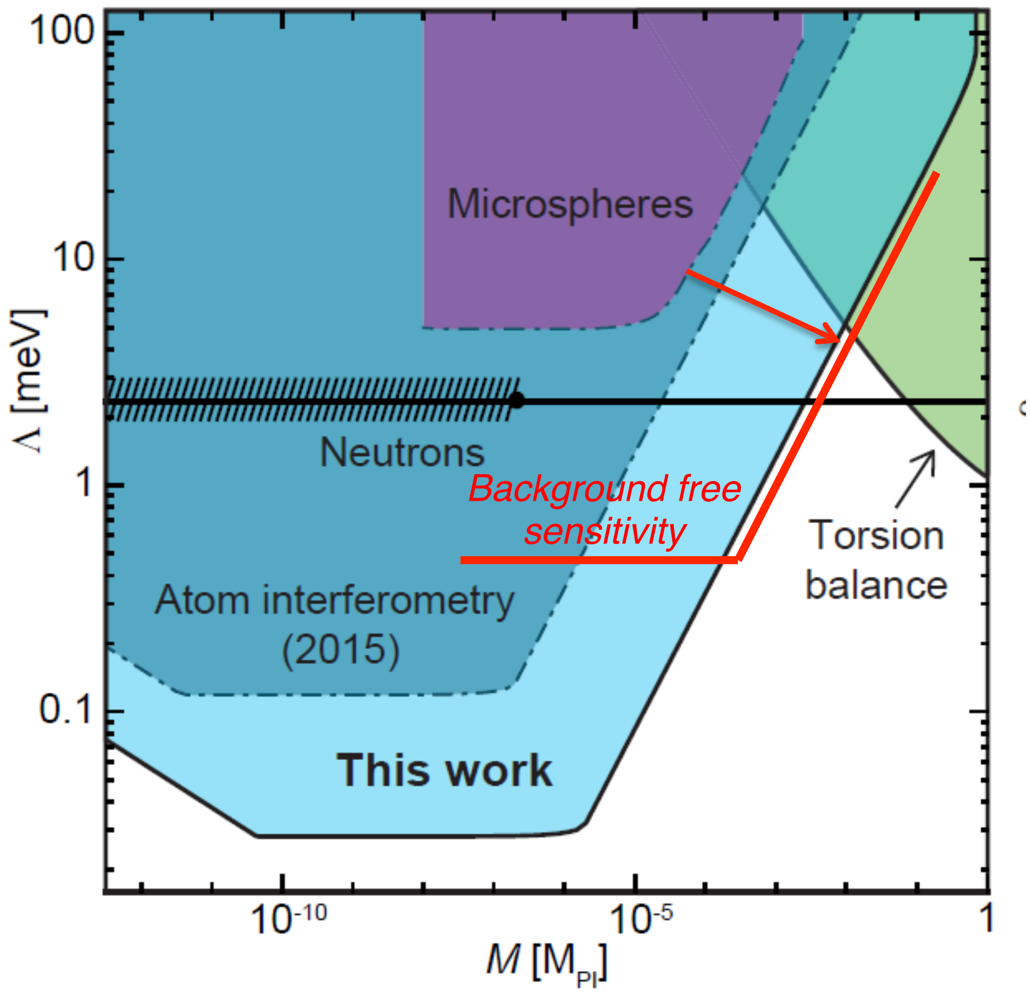
- Consistent with background-only model at 90% CL
- Sensitivity limited by electrostatic backgrounds, and unable to constrain models with Λ = 2.4 meV due to self-screening
- Constraints can be set at Λ > 4.6 meV where self-screening is reduced



Background free sensitivity

- If backgrounds could be eliminated, substantial improvement in sensitivity might be possible

Updated constraints on chameleon interactions:



Plot from talk this morning from H. Müller

Possible improvements:

Spin μspheres

Measure and cancel contact potentials

Improve probe mass design

Dark photons

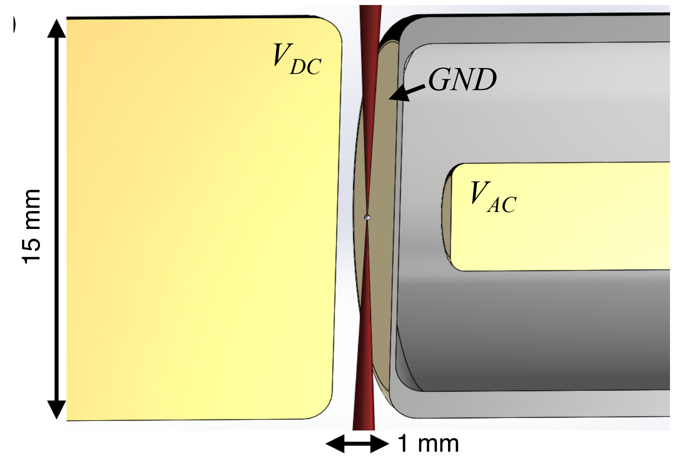
- Tests of Coulomb's law can search for new forces from a dark sector (e.g. dark photons)

Dark photons: $$V(r) = \frac{e^2}{r}\left(1 + \chi^2 e^{-m_\Gamma r}\right)$$

Light millicharged particles: $$V(r) \approx \frac{\alpha}{r}\left[1 + \frac{\alpha\epsilon^2}{4\sqrt{\pi}} \frac{\exp(-2mr)}{(mr)^{\frac{3}{2}}}\right]$$

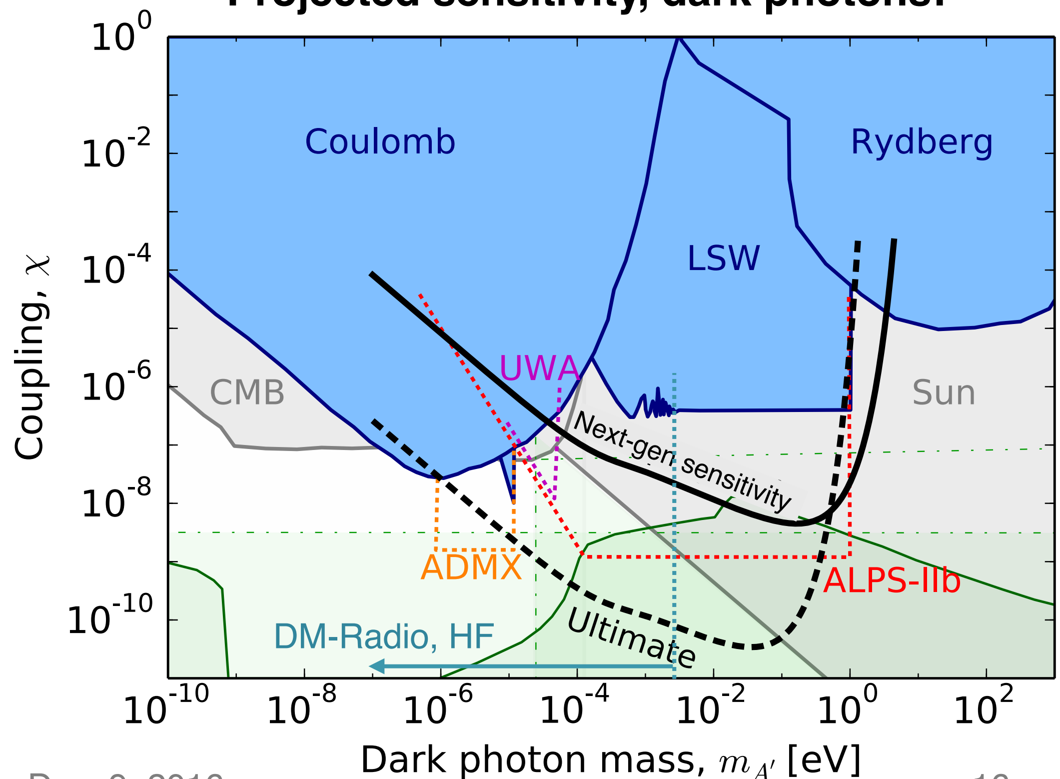
e.g. Jaeckel and Ringwald, Ann. Rev. Nucl. Part. Sci., ***60****, 405 (2010)*

Schematic of electrodes:



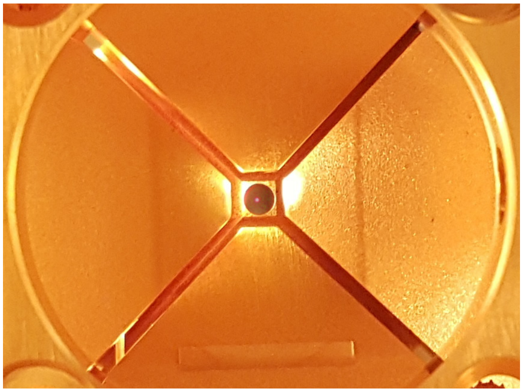
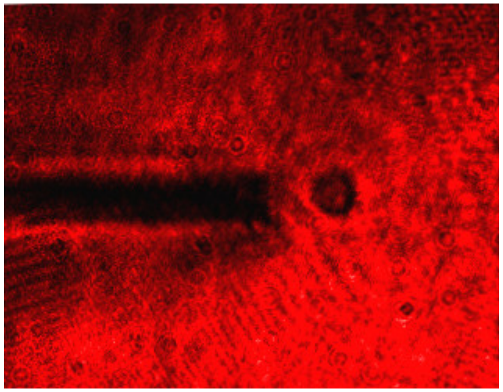
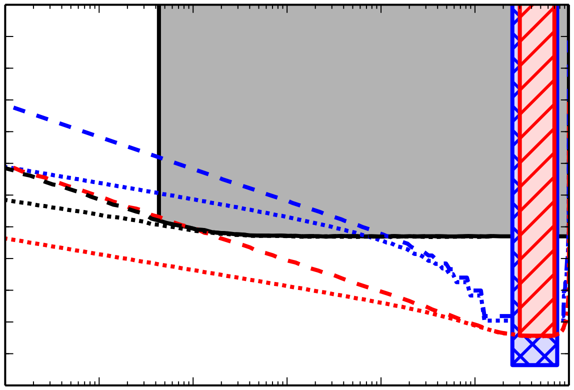
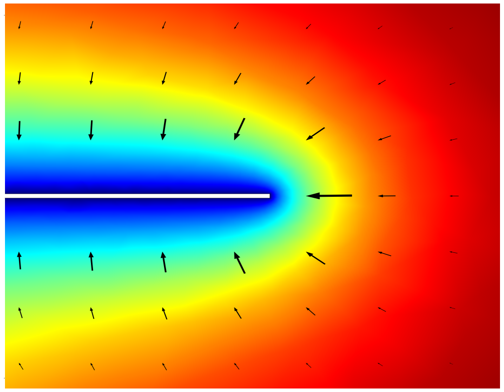
- Most sensitive to meV-eV mass range
- Ultimate sensitivity could reach DM models below solar limits
- Complementary to "light shining through wall" experiments and DM-Radio

Projected sensitivity, dark photons:



Summary

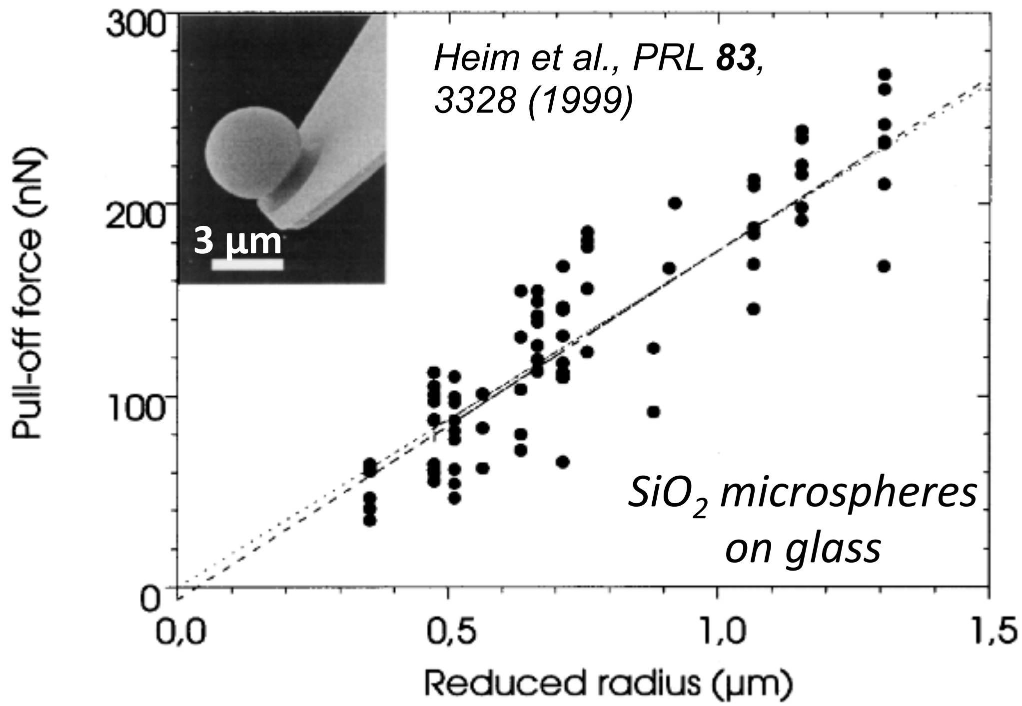
- Levitated microspheres in high vacuum provide a sensitive probe for new forces at distances << 100 μm
- Have performed sensitive searches for millicharged particles and screened scalar dark energy models
- Next-generation searches will further improve sensitivity to tiny fractional charges and forces mediated by dark photons
- In parallel, these techniques will test the ISL for gravity at micron distances
- Other applications to search for dark sector physics may be possible as these techniques are further developed!

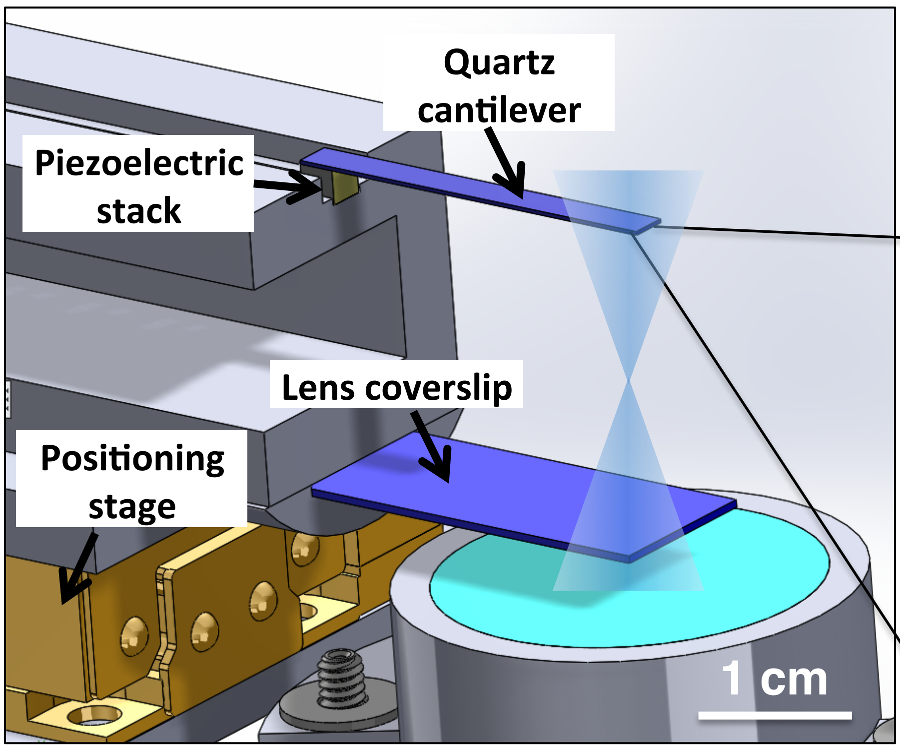
Trap loading

- Microspheres are launched from bottom surface of quartz cantilever
- Pull-off forces of ~100 nN require accelerations ~10^6 m/s^2
- Bottom coverslip protects lens and is retracted after trapping

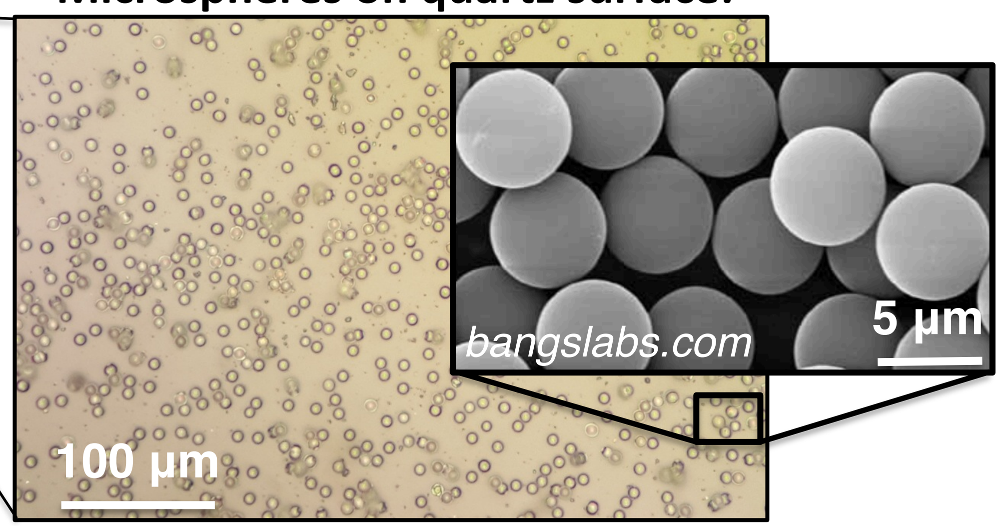
Pull-off force vs. microsphere radius:



Schematic of microsphere dropper:



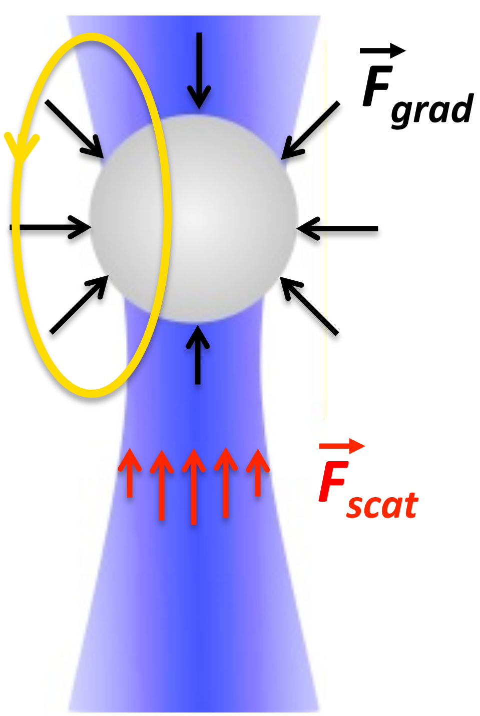
Microspheres on quartz surface:



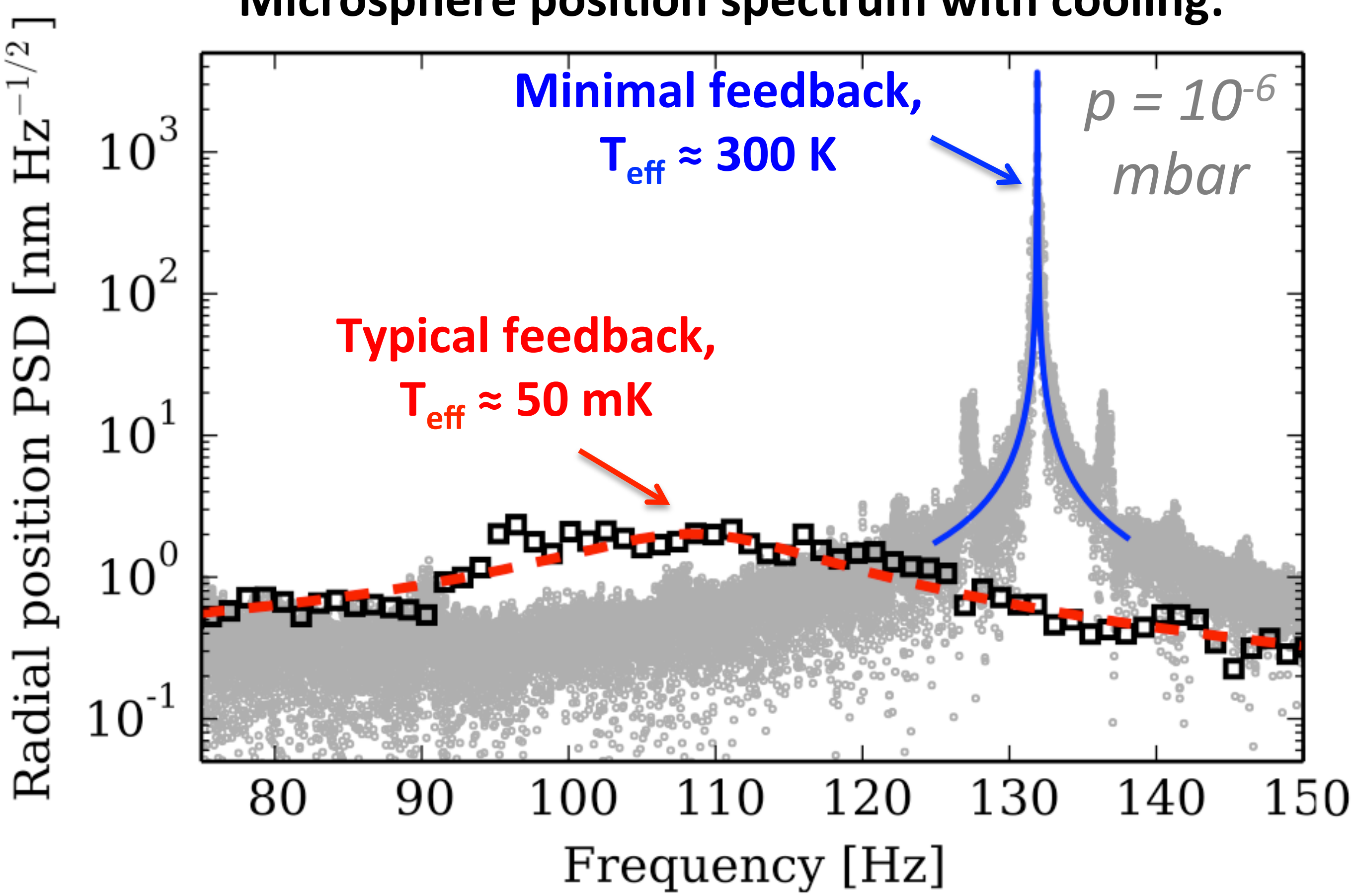
Microsphere cooling

- Below ~1 mbar, active feedback cooling is needed for stable trapping
- Monitor position of microsphere and modulate amplitude and pointing of the trapping beam
- Can cool center of mass motion to < 50 mK in all 3 DOF

Mechanism for laser heating:



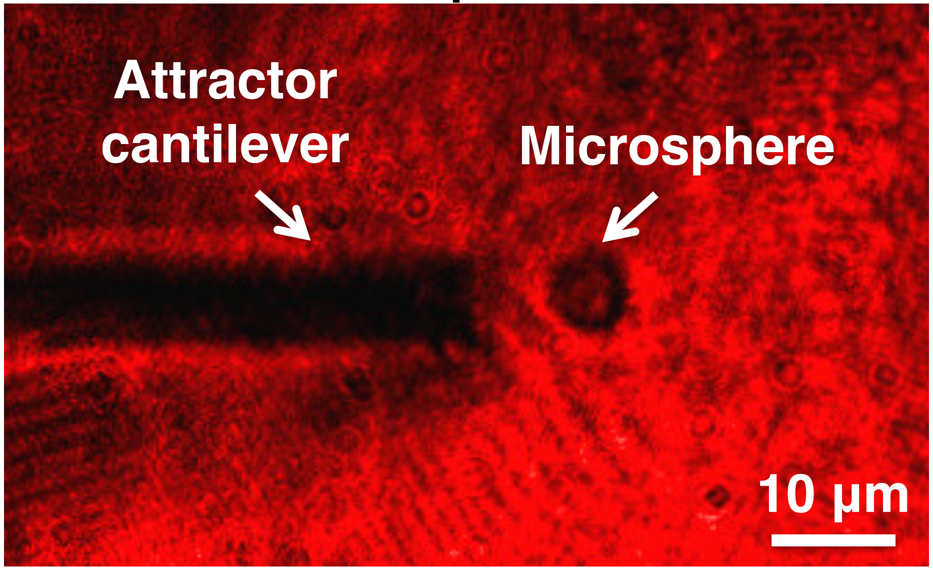
Microsphere position spectrum with cooling:



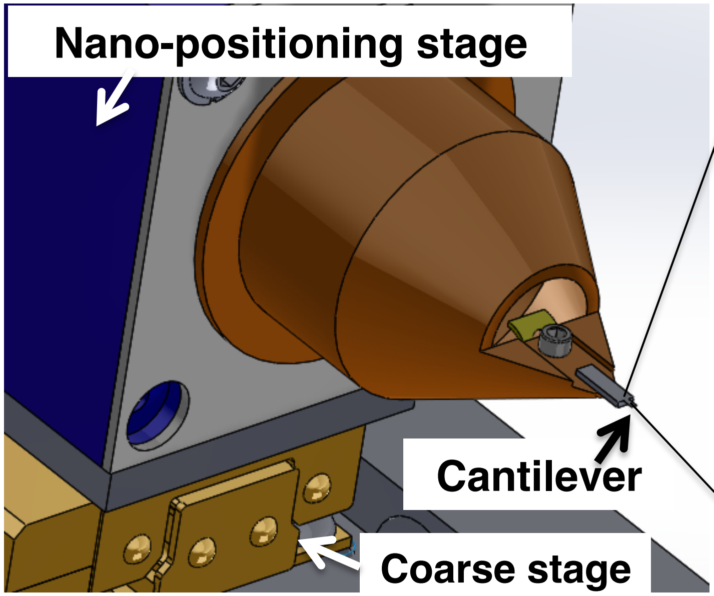
Attractor

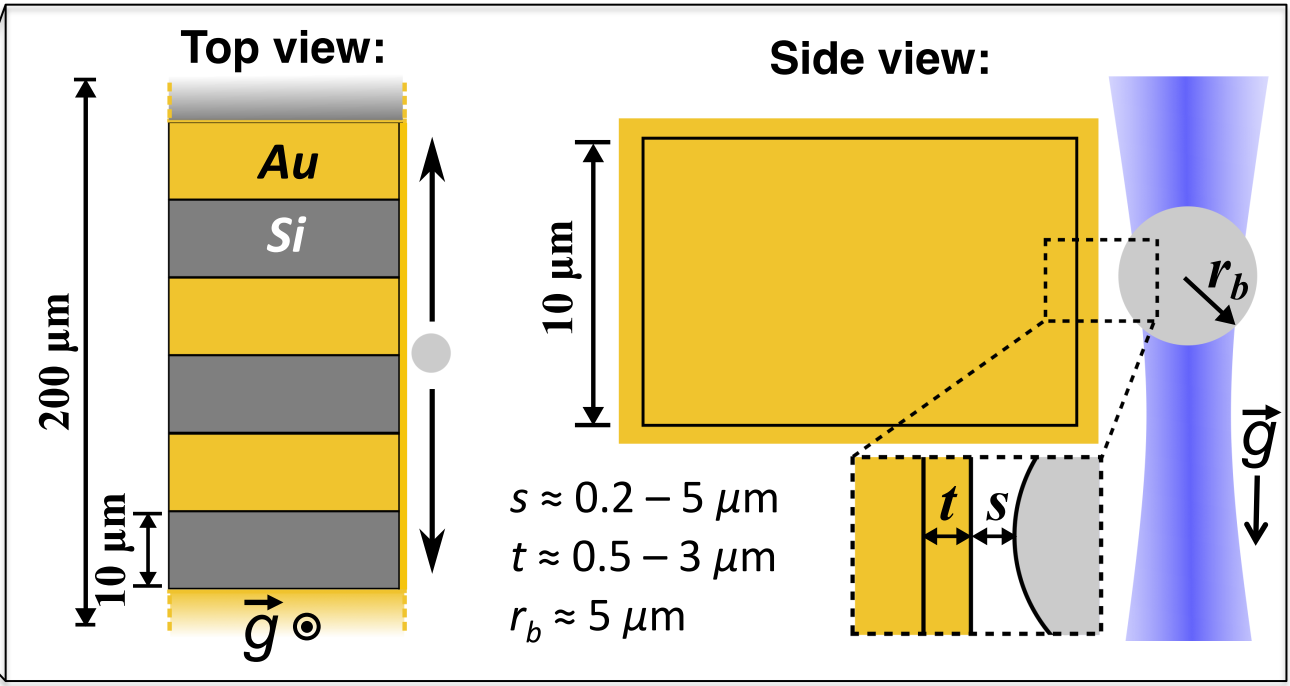
- Need attractor that can be placed at ~µm separations from microsphere
- Spatially varying density allows reduction of backgrounds
- Stage allows cantilever to be swept ~100 µm in all 3 DOF at >10 Hz

Side view of microsphere near attractor:



Schematic of positioning stage assembly:

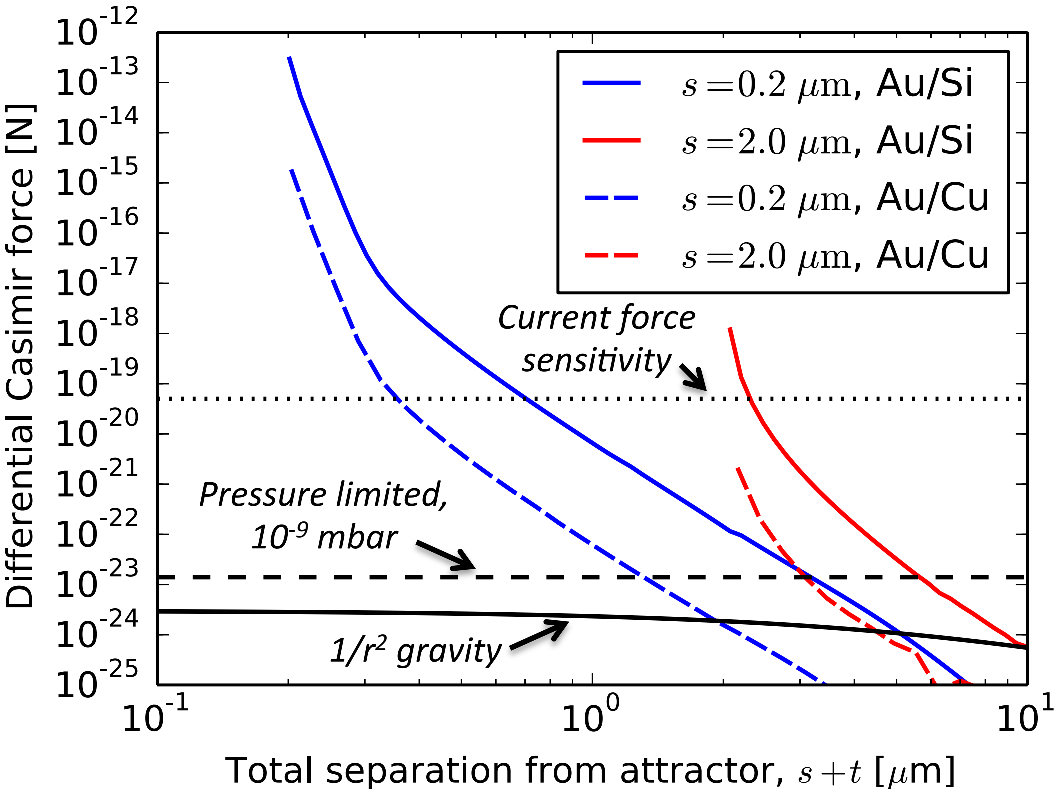




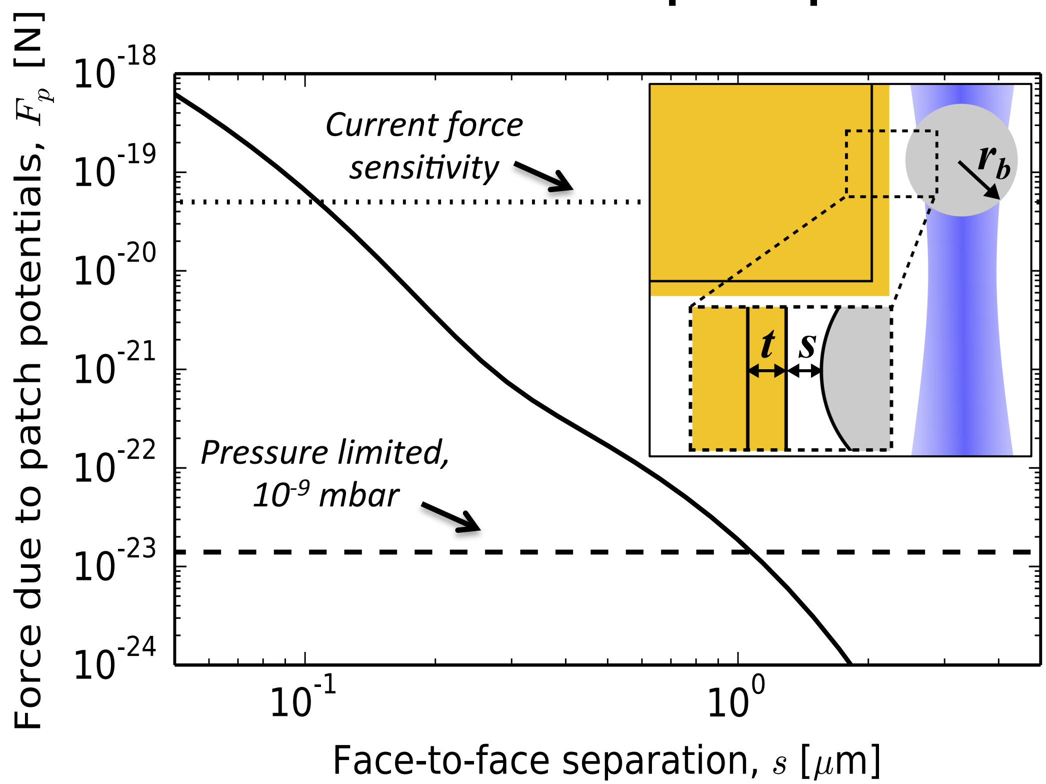
Expected backgrounds

- If unscreened, differential Casimir force between Au and Si can present dominant background
- Coating attractor with Au shield layer (0.5 to 3 μm thick) can sufficiently suppress this background
- Background due to surface "patch potentials" should be subdominant for expected face-to-face separations

Calculation of differential Casimir force:



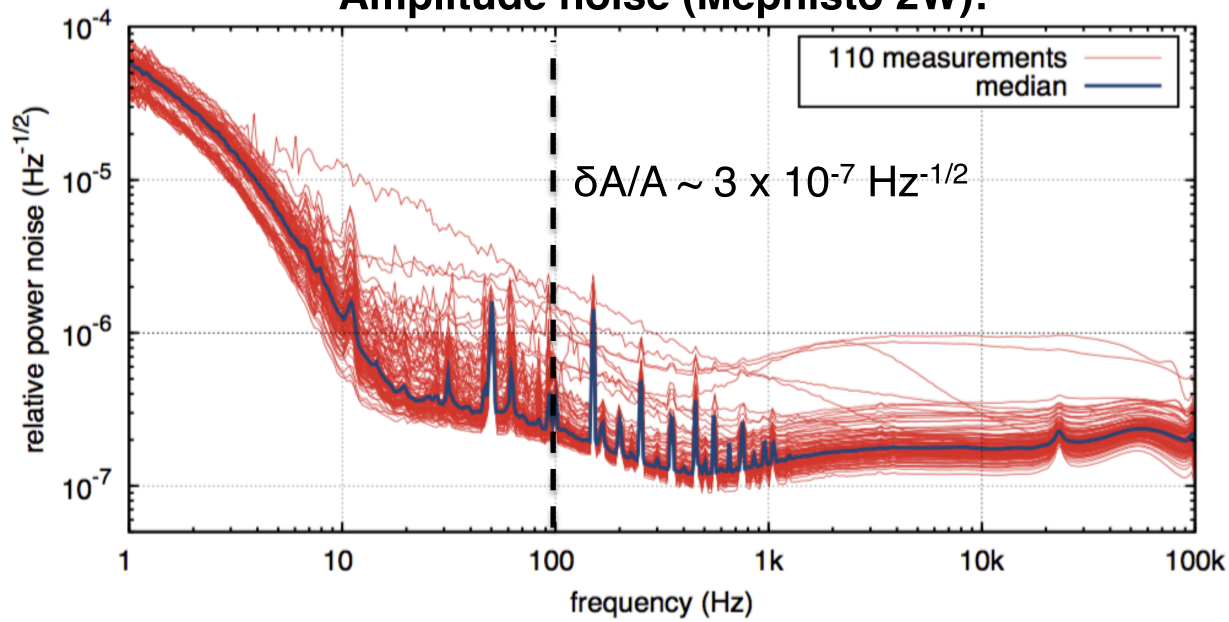
Calculation of force due to patch potentials:



Laser noise

- For r > 1 µm spheres, thermal noise can be made negligible at low pressure (below SQL at $p \sim 10^{-10}$ mbar)
- Technical sources of noise dominate in existing experiments
- Even NPRO Nd:YAG lasers developed for LIGO 1st stage require additional stabilization

Amplitude noise (Mephisto 2W):



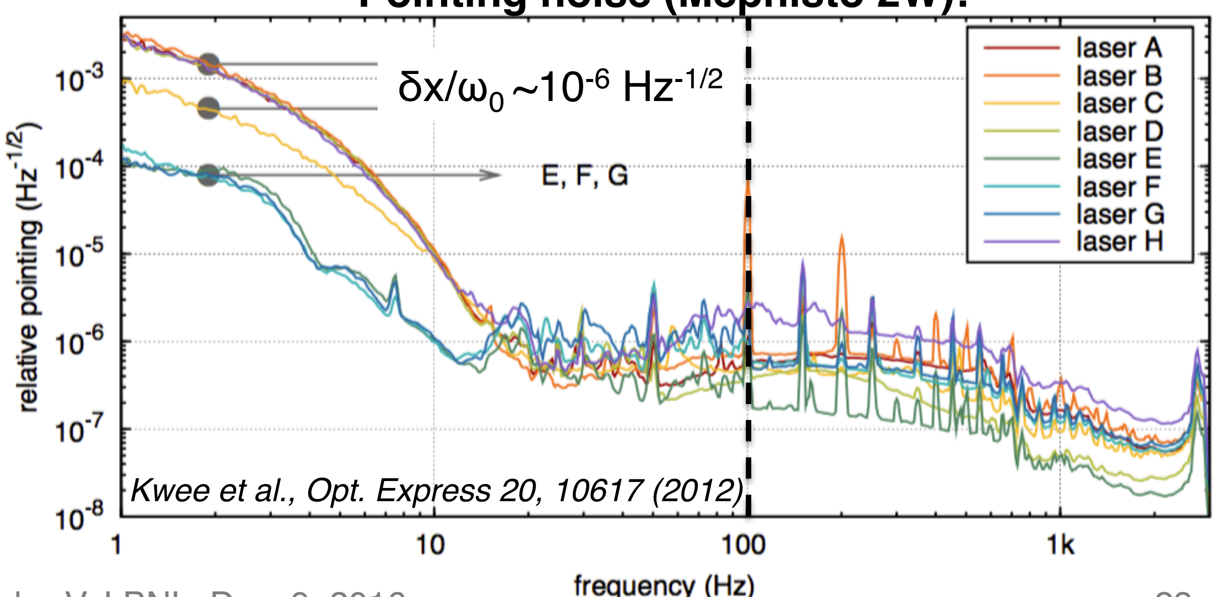
Pointing noise limit (Mephisto):

$$\frac{\delta x}{\omega_0} \sim 10^{-6}\ \mathrm{Hz}^{-1/2}$$
$$\Rightarrow \delta F \sim 10^{-19}\ \mathrm{N\ Hz}^{-1/2}$$

~100x improvement over current sensitivity

~50x worse than SQL

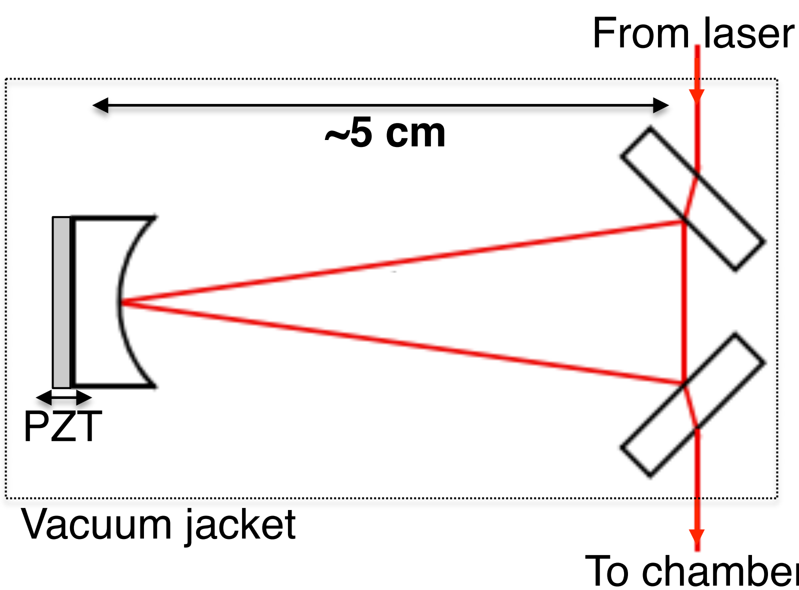
Pointing noise (Mephisto 2W):



Mode cleaning

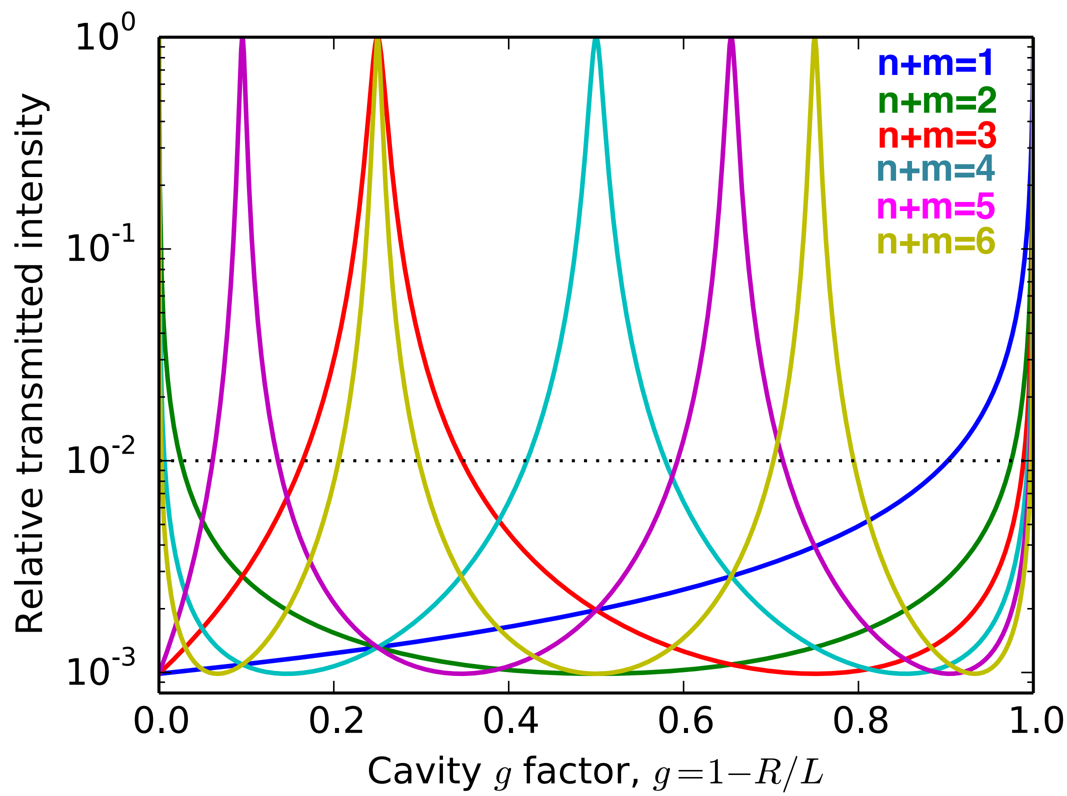
- Output of laser can be stabilized by active feedback and passive mode cleaning cavity
- Stabilization to requirement at SQL for $F \sim 50$ external mode cleaning cavity
- Will also test coiled single mode fiber as mode cleaner

Schematic of ring resonator mode cleaner:



Vibration stabilized ring-resonator similar to LIGO output mode cleaner

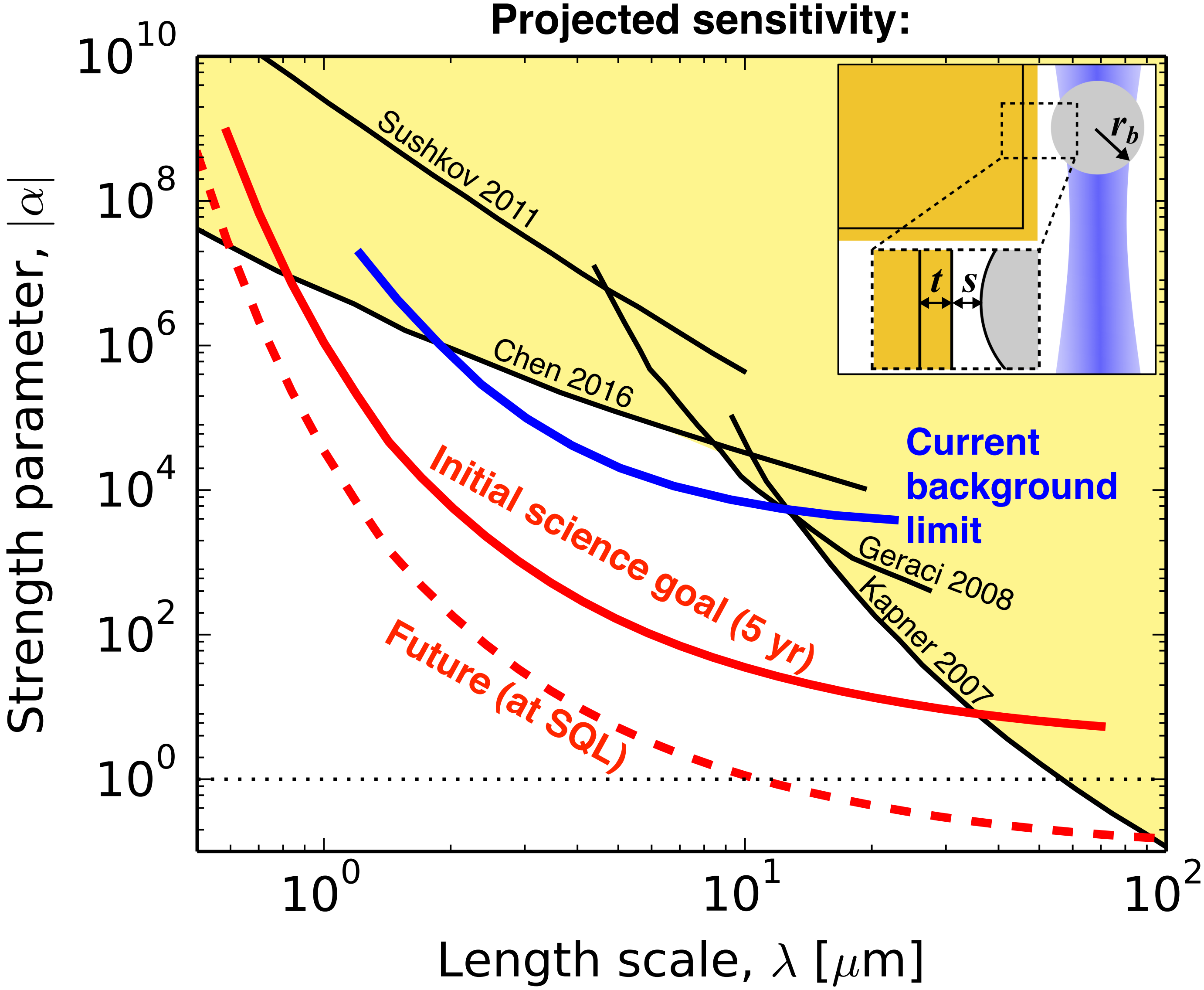
Transmission of higher order modes, *F* = 50:



Sensitivity at SQL

- Reaching SQL would allow substantial amount of explored parameter space to be searched for new gravity-like interactions!

Projected sensitivity:



Assumptions:

r_b = 10 μm, optimized for λ~2-100 μm

Face-to-face separation, s = 5 μm

Au shield thickness, t = 3μm

$\tau = 10^5$ s integration

5 yr goal:

$\sigma_F = 5 \times 10^{-19}$ N Hz$^{-1/2}$

Future (at SQL):

$\sigma_F = 2 \times 10^{-20}$ N Hz$^{-1/2}$

Assumes shielded attractors suppress backgrounds below projected noise level